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Title Sub. Atoms. 1933.

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THE SUB-ATOMS

AN INTERPRETATION OF SPECTRA
IN CONFORMITY WITH THE PRINCIPLES
OF MECHANICS

BY

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BALTIMORE

THE WILLIAMS & WILKINS COMPANY

1933

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Made in the United States of America

Published December, 1933

COMPOSED AND PRINTED AT THE
WAVERLY PRESS, INC.
FOR
THE WILLIAMS & WILKINS COMPANY
BALTIMORE, MD., U. S. A.

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PREFACE

Elementary works introducing discussions of atomic structure from the attitude of the quantum theory quite frequently assert that Newtonian mechanics has failed to elucidate atomic structure, giving this as the chief reason why the older ideas of mechanics should be discarded and other ideas adopted in their stead, in this, and allied fields of science, whose chief data are derived from spectroscopy. Such statements are most prejudicial to sound judgment. The truth is that in the field of atomic structure, and in the interpretation of spectra, Newtonian mechanics has never been consistently tried. Let any who doubts this produce the records of the supposed trials. The schemes that have been tried have all introduced assumptions that do not appertain to Newtonian mechanics, but on the contrary, propose amendments thereto.

When anything is declared impossible of accomplishment, the most convincing way to prove its possibility is to do it. In the following chapters the writer has applied Newtonian mechanics to the interpretation of certain spectra, without introducing any amendatory postulates. Such application has led to very definite suggestions about the structure of atoms, which differ fundamentally from those assumed in the past, as bases for investigations. The atoms of the elements are found to be aggregations of smaller units, which the writer has called sub-elements, in much the same way as chemical compounds are aggregations of chemical atoms. Certain definite dimensions of these sub-atoms are revealed. The numerous spectra ascribed to atoms owe their variety to the varieties of combinations of sub-elements which are formed when atoms are broken by electrical or other excitation.

Those who do not wish Newtonian mechanics to be successful may find this book annoying, the writer ignorant of "established principles" of modern physics, and not qualified by training to consider, much less to discuss such matters. Such men wish to start with the assumption that atoms are not composed of particles, in the sense that Newton used the word, and the word is understood by ordinary men. They wish something sacrosanct in the structure of matter,

which only the mathematically initiated can profess to understand. They are intolerant of the intellect of the ordinary man. The writer of this book does not deny his ignorance, or boast of his qualifications. The claim of this work to a hearing is not based upon such considerations. Regardless of their origin, the ideas here presented are entitled to the consideration of all leading physicists because of the injustice and folly of setting aside without adequate trial the ideas of the greatest mathematical physicist the world has yet seen, Isaac Newton, as inapplicable in the field which he himself most hoped that they would ultimately come to dominate.

I wish to express my thanks to those who, without regard to whether they agreed with me in point of view, assisted me materially in securing data during my studies, particularly the study of hydrogen spectra, or encouraged me in this work by other means, especially to Prof. Thomas R. Merton, of London, England; Prof. O. W. Richardson, Yarrow Research Professor, London; Prof. J. C. McLennan, formerly of the University of Toronto; Prof. K. T. Compton, President, Massachusetts Institute of Technology; Prof. F. K. Richtmyer, Cornell University; Prof. Manne Siegbahn, Upsala University, Sweden; Prof. Charles Skeeel Palmer, Pittsburgh; Mr. E. H. McClelland, Carnegie Library, Pittsburgh; and Mr. Albert L. Clough, Manchester, New Hampshire.

WILLIAM MAYO VENABLE.

Pittsburgh, Pa.
October, 1933.

CHAPTER I

MATHEMATICS AND MATTER

A certain tribal chieftain in prehistoric days had a herd of cattle which he desired to have counted. He arranged two fences converging to a narrow passage, through which the cattle were driven in single file. Two counting men were stationed beside the passage, and kept tally of the animals on their fingers and toes, as the beasts were driven by. Upon completion of the count both men reported independently that the number of cattle was equal to the number of fingers and toes on six men, and four fingers more, or as an Englishman might say, six score and four. The chief considered it in no way remarkable that the men agreed in the count; in fact he would have been angry if they differed, for he had progressed to that stage of culture where he had an idea of abstract number, and if the two counting men had disagreed he would have felt sure that one or both of them had erred, or been dishonest, rather than that there was any lack of precision in the number of cattle in the herd.

This chieftain had another herd, and the count of that herd was two score and nineteen. The counting men were instructed to ascertain how many cattle there would be altogether when the two herds were united. They did not combine the herds and make a recount, but performed the addition entirely on fingers and toes, and announced the correct sum—nine score and three.

Long before the dawn of any civilization of which we have record men knew that this art of counting could be applied not only to cattle, and other possessions, but even to things of an intangible nature, such as the days of the year. Addition and subdivision belonged to an exact science, and computations made by the aid of counters could be applied to the numbers of objects of any kind, however different from the counters used for the tally. One finger or one toe is equal numerically to one cow or one day, though not comparable in any other attribute than number. Sticks or stones would answer for the counters as well as fingers or toes. In time an abacus or a rosary was found more convenient. Thus, while ever verified by counting objects, the counting and computing art, which we now know as arith-

metic, became altogether independent of the nature of the things counted, and assumed a universality co-extensive with certain kinds of experience. While wholly confirmed by experience within the limits wherein experience appeared possible, it no longer seemed to be dependent upon experience, but something abstract and eternal which transcends all experience.

It is possible to make a perfect count, no matter how great the number of things counted, if sufficient time is allowed for the counting process and the things to be counted are discrete and separately perceptible. Of course it also is possible for the counting man to be inattentive, or to neglect to record his tally, or to cheat; but there is nothing in the counting process per se that requires an error, or even excuses one. The only judgment required of the person who makes the count is distinguishing between this and that. The problem is different if the counting man is told to make one count of the full grown cattle and one of the calves. Two men should agree exactly as to the total number of cattle, but might excusably differ as to whether or not an animal were or were not full grown. The error would not be one in the counting process, but one in discrimination as to size.

Arithmetic deals exclusively with relations of numbers, and is not concerned with the accuracy of counting in any particular instance. Because of this arithmetic is an ideal and mathematical science; but owing to the fact that counting may be accurate, arithmetic may be applied to real problems with absolute accuracy, in all cases where the problems deal exclusively with experiences which may be counted, and do not involve judgments of other things or attributes than number. We may call arithmetic the first of the mathematical sciences, and probably it is the oldest, and its basic principles least subject to dispute. The concept number, however, is not the only one in which quantitative comparisons may be made. We readily perceive that countable objects manifest differences in size, and in other attributes, which are capable of comparison, or approximate measurement. To such attributes also mathematical sciences may be applied, but these other mathematical sciences are capable of application to nature with somewhat less accuracy than counting, or arithmetic, and it is necessary that we shall appreciate the restrictions in their applications in order that we may judge fairly as to the extent to which the other mathematical sciences are founded in ex-

perience and the extent to which they are based on ideas that experience cannot verify.

Let us suppose that our tribal chieftain owned more cattle than he needed, but insufficient land to pasture them; and that he had a neighbor possessed of more than enough land, but insufficient cattle; that the two were friendly, and desired to effect an exchange, or barter. The cattle to be transferred could be counted; but it required a very different procedure to apportion the land. At first such transfers must have been made by boundaries only, such as streams and mountain ridges. Later, measurement was resorted to, and measuring units established. This required a new mathematical science, which still bears the name Geometry, which means land measuring. Even now the measurement of land is a difficult matter if we strive for accuracy, and in very ancient times when there were no standardized units of length more accurate than the span or the pace, or of areas more accurate than that covered by the hide of a bull, mathematical geometry, based upon empirical geometry, was scarcely possible. Indeed, long after more accurate standards were introduced, geometrical rules remained empirical. Among the recently discovered records of ancient Egypt is a document giving instructions for calculating the volume of a pyramid. It reads more like a receipt in a modern cook book than a proposition in abstract geometry, but it leads to the correct answer quite as well as if couched in abstract terms and ending with Q.E.D., instead of "you will find the answer correct."

Abstract, or precise geometry, is said to have been originated by Thales of Melitus, who is credited also with having predicted the solar eclipse to which we now give the date May 25, 585 B.C. This tradition may or may not be true; but it is certain that abstract geometry became very highly developed among the Greeks, and that its devotees were greatly respected. The basic principles of precise, or abstract geometry were collected and codified by Euclid, whose books still supply the outline of the science as taught in modern schools; while Apollonius of Perga, who was born B.C. 262, wrote a book carrying the subject much farther than the modern high school student ever goes, including 387 propositions in conic sections.

We have seen that the counting process may be carried out with absolute accuracy, within a limited range of experience. This is not true of any process of measurement. If any unit be taken as a stand-

ard, for instance, a yard stick, and a lad to be told to measure out with it a length of one hundred yards from a given point, in a designated direction, and place a marker, and if we then give the same yard stick to another person and have him measure out a like course in the same direction, we will find that the two measurers will not have placed their markers at exactly the same point,—nor indeed will the same person repeat his measurement and obtain exactly the same result. We are in the habit of ascribing such discrepancies to error on the part of the person who makes the measurement. By using very accurate measuring instruments, well trained observers, and exercising many precautions to eliminate errors we may have a series of such measurements tally with one another very closely, but never perfectly, though the variations may be small. Geometry, based upon measurement exclusively, never could be absolute, or perfectly accurate, on account of the limitations of our senses. We can render geometry absolutely accurate only by considering that all of the inaccuracies incurred in measurement are due to *errors*, and that although perfect measurements are impracticable, perfect comparisons of length and other spatial attributes are possible *in the ideal*, which we call space.

If we place a sheet of paper on a flat table and draw upon it a triangle, we can by measurements convince ourselves that the sum of the lengths of any two sides is never exceeded by the third side. But if we state that the sum of the interior angles of a triangle is always *equal* to two right angles we are stating something more than our experience can verify, unless we add the proviso—as nearly as we have been able to verify by measurement, using the instruments available. We do not require such a proviso in arithmetic as long as we are dealing with numbers that we can count. In order to make geometry an exact science to which arithmetic may be applied it is necessary to assume that there are, ideally, geometrical equalities, in such attributes as length, angles, and areas.

If experience teaches us that the sum of the three angles of a triangle is equal to two right angles as nearly as we can ascertain by all the means at our disposal, we may postulate that in space the sum of three angles of a triangle is always equal to two right angles. This makes our ideal, which we call space, precise and mathematical, even if we have no means of measurement.

Geometry, built on the idea of space to which this, and other postu-

lates of similar origin apply, is the ideal geometry of the Greeks, as well as the practical geometry of modern engineering, for experience teaches us that in all of our practical engineering this kind of geometry can be used to perform calculations referable to nature without involving us in error greater than can be ascribed to errors of measurement. It is, however, possible to conceive that in actual practice our ability to make accurate measurements might become greatly extended, and that we should then find that, when we measured very large triangles, the sum of the three angles, as measured, always exceeded two right angles by amounts which, because of their smallness, or the small sizes of triangles hitherto measured, we have hitherto not succeeded in detecting at all. In such an event, if we desired to apply an ideal geometry to our new observations, we would have two options. The first would be to use our ideal Euclidean geometry, and apply a correction for triangles of larger size than those to which we are accustomed. The second would be to develop a new ideal geometry in which the postulate would be modified, possibly in some complicated way which we could only discover by new measurements on scales much vaster as well as much smaller than any which we have used in the past. We would have to know some mathematical law that would inform us, in the case of each triangle, how much greater or less than two right angles the sum of the three internal angles of the triangle under consideration may be. The two systems, under these circumstances, would give the same practical results,—the Euclidean system modified by a correction, and the new ideal system which embodies the correction, though professing to rest upon a different theoretical basis.

In considering other kinds of ideal space than the Euclidean (which also is the Newtonian ideal) we must bear in mind that, for ordinary space measurements under terrestrial conditions, if there is a systematic departure from two right angles in the sum of the three angles of a triangle, the departure is too small to measure. Consequently we incur no measureable inaccuracy in our engineering practice by using the Euclidean ideal, which has the great advantage of developing mathematical expressions of greater simplicity for such problems than any of the non-Euclidean ideals. On the other hand, we have not stretched a tape line across the Earth's orbit, or put surveyor's stakes in the space between the Earth and the Sun. All of our astronomical lengths are determined by computations based

upon terrestrial lengths, and all of our terrestrial lengths are measured with instruments which are compared with one another only on the basis that space is Euclidean. If space is not Euclidean we can detect the curvature thereof only as discrepancies between measured and calculated distances, the measurements all having been made with standards which are, as nearly as our sense perceptions have as yet informed us, Euclidean.

These remarks are not made to prove that there is objective space that corresponds to our Euclidean ideal, or the converse; nor is it the intention to discuss the metaphysical problem as to whether space is purely ideal, and has no objective existence outside of consciousness. They are made in this connection for the purpose of pointing out that we may have precision in our conception of an ideal science, such as geometry, even though we cannot have absolute precision in measurement, or even precision sufficient to prove that there is objective space that corresponds exactly with any ideal.

Time, also, is a concept with which, with number and other attributes, such as space, we may deal mathematically. The simplest judgment we can form involving any attribute of time is whether an event happened before or after another event,—a matter of sequence of events. Our evidence of sequence arises from the fact that we remember experiences in a certain order, and others likewise remember the same events in the same order. The mathematician may argue that he does not need the conception of before or after in dealing mathematically with certain thermodynamic phenomena, or the theologian may insist that to Divinity all events belong to an *eternal now*, but these arguments in no way modify our experience of a time sequence which to us is irreversible. The measurement of time is even more difficult to establish with philosophical accuracy than measurement of length. It depends upon the measurement of lengths, as the distance moved by the hands of a clock in the time interval between events, or the recurrence of events which we believe to be regularly spaced in time, like sunrise, or the swings of a pendulum. But in spite of all difficulties that arise in the accurate measurement of time intervals, especially between events that are separated by vast distances as well as vast time intervals, we are able to think of time, as we are of space, as divisible into equal intervals that may be treated mathematically, in mathematical relationships with spatial attributes.

The simplest kind of mathematical time which we have conceived is that in which equal intervals may be taken, and the flow is uniform, no matter how small the intervals may be taken. It is that kind of time which makes it possible to consider uniform velocities and uniform accelerations. Such ideal time, with some equally ideal space, and number, supply the framework for a mathematical scheme which can be applied to nature. With Euclidean space it provides the framework for all of mathematics prior to the time of Newton. These concepts did not suffice to interpret all of the relationships between phenomena, but only certain kinds of relationships between certain kinds of phenomena. These are the concepts which Newton found available, but not sufficient for mechanics, and to them he added a new concept, or rather reduced another concept to mathematical precision, in order to make mechanical phenomena mathematically calculable to a greater extent than before,—not in absolute conformity with nature, but with absolute precision within the absolute system itself. Thus he created the new mathematical science, Mechanics.

All of the concepts necessary for mathematical thought involving number, space and time, or any of their elements or attributes, were well known before the time of Newton, and it was known that space and time can be thought of as separate and independent of one another, as well as in relation to one another, as is necessary when we consider such ideas as velocity and acceleration. To these elementary ideas Newton added the idea of another concept, measurable, and likewise capable of being thought of separately,—mass. He conceived of mass as an attribute of particles, and of a particle as a discrete, countable unit of matter. In his conception the mass of any discrete body is the arithmetical sum of the masses of all of its particles. To introduce this conception mathematically it was necessary for him to be precise in his conception of the relationships between a particle and the other mathematical attributes, time and space. Accordingly he defined the species of mathematical relationship between time and space which he proposed to adopt for mathematical purposes in the new science. Newton was not defining our experience of time or space; that is a matter which involves our capacity for understanding; nor was he defining absolute time or space aside from their mathematical attributes. He was not concerned with the question whether time and space have separate

real existence, or could be apprehended if no matter were in existence. On the contrary, he was stating definitions to be used mathematically, for computations, in an ideal system which experience proved to him could be used for the purpose of computing natural phenomena as accurately as, with our limited capacity for measuring, the same phenomena could be measured with comparison standards available to us.

For this purpose he added to the definition of space that, in his ideal mathematical system it should be considered as fixed,—that is, immovable with reference to itself. All motion in his system was to be ascribed to particles, or their aggregations. If we like we may consider this an arbitrary restriction, or if we prefer we may consider it a logical necessity; but in either event it is a mathematical convenience for many mechanical problems, especially for the problems of rotating bodies and systems of bodies, with which, in the details of his work, Newton was greatly concerned. Newton was fully aware that the mathematical laws relating to moving bodies which he proposed to enunciate could be expressed exactly with reference to ideal Euclidean space which was conceived to be moving uniformly in one direction without rotation, but knowing that the rotational problems could be treated more simply if space were considered as non-rotating, he chose the simplest variety of space concept in which space itself was not only not rotating, but free from all motion. Just as the geometrical equation for a circle is simpler if we take the center of the circle as our reference point, in preference to any other point, so the general equations of motion are simpler if we frame them with reference to space at absolute rest rather than with reference to space that has some motion with respect to itself or some of its own attributes. In following this course Newton was merely following the advice he gave others, to use no greater number of attributes in explaining any phenomenon than were required by the nature of the phenomenon observed,—a principle that may be greatly abused if in seeking to simplify a problem a mathematician leaves out of consideration some attribute which ought to be included. For convenience and clarity, therefore, as well as because he was ascribing mobility to particles, Newton defined his mathematical space not only as Euclidean but also as immovable. He also implicitly included the condition that space is indefinitely divisible into equal units, and does not of its own nature exist in discrete parts. Time

he defined as flowing uniformly, not with reference to space, but with reference to itself. Mathematically, this means that the sequence of events in time cannot be reversed, and that time may be divided, for mathematical purposes, into equal intervals, of any desired length; but that these intervals cannot be separated from one another, or taken out of their mathematical sequence.

All discrete parts in nature considered by Newton in the system of mechanics are particles of matter. The system therefore excludes, by definition, discrete things, if there are any such, which do not possess the essential attribute of matter, mass. Unless we can show that a soul has mass, by weighing it, or giving it mechanical motion, we cannot include souls in mechanics. It is well to remember that Newton's definitions, or at least his conceptions of mechanics have inherently such restrictions. Each particle of matter occupies some space—that is, it has volume, as well as position and motion in space. But every particle of matter possesses an attribute which space and time as conceived by Newton do not have in any degree whatever.

This is the attribute termed mass. By virtue of mass a particle naturally tends to continue unchanged in its motion with respect to our ideal fixed space, unless it is acted upon by some other particle or particles of matter. Thus conceived, mass is an inherent quality. It does not depend at all upon the interaction of particles. It is defined with reference to ideal space and ideal time, not with reference to observed changes in the motions of different bodies. It is particularly necessary if we are to understand Newton, for us to realize that mass, in his mechanical system does not depend upon gravitational attraction, or the laws of impact. We must keep the abstract mathematical ideal quite distinct from all matters having to do with our ability to measure, or to make comparisons.

Newton's system, like the geometrical systems which are closely related to it, is intended to be applied to nature. The question whether its fundamental ideas, as well as its special preferred "system of coordinates" or "frame of reference" correspond with nature can only be determined by making accurate measurements of natural phenomena with respect to each other, and interpreting them by means of the ideal theory. Discordances between theory and measurements may be due to either of two causes, or to combinations of both,—inaccuracy in the measurements or omission to measure and to take into account all of the factors affecting the measured phenom-

ena, and inaccuracy or falsity in the theory. If the discordances are less than the possible errors of measurement and the omissions, the theory is not discredited legitimately; but if there are systematic discordances either the theory must be wrong or some factors have been systematically ignored. It may be very difficult to tell which is wrong, but whenever we take the position that the discordances are systematic and no factors have been overlooked or ignored in the mathematical treatment we can no longer consider the theory a correct interpretation of nature.

In our studies of ordinary mechanical movements, such as are dealt with in practical problems of engineering for industrial purposes, we find no systematic discordances between Newtonian mechanics and practical measurement such as indicate defect in the theory or serious omission of any factor in the treatment of problems. In astronomical studies, however, there are discrepancies between the observed motions of certain planets and the motions to be expected on the basis of calculations which take into account the attractions exerted upon each planet by the Sun and by all other planets. These discrepancies are small and apply chiefly to the inner planets. The discrepancy is greatest for the planet Mercury, which is closest to the Sun. Planets do not move around the Sun in perfect ellipses, although were there only one planet and no disturbing influences upon it, it would be expected to move in a perfect ellipse. The actual orbits resemble ellipses, which slowly rotate about the Sun. The amount of this rotation of the orbit is something which can be determined from observed orbits, if the orbits have been observed for a sufficient period of time. It is also something which can be calculated by Newton's law of gravitation, if all of the planets are taken into account, instead of only one planet and the Sun. This discrepancy between the observed and the calculated rotation of the orbit of Mercury amounts to a few seconds of arc in a century.

This discrepancy, though small when judged by ordinary standards, is greater than the probable errors of measurement, and is considered real by all competent astronomers who have studied the matter. It is of the kind that would be expected if the Sun were a little heavier with respect to the Earth than it is with respect to Mercury. It might be interpreted, therefore, as due to either of two causes,—that there is matter between the Earth and the orbit of Mercury, that attracts the Earth, and thus makes the Sun seem heavier than

it does to Mercury, in which case the Newtonian system may still be correct, or that the Newtonian theoretical system is in error, of such a kind that this discrepancy should be found when applying it to this particular case. If we adopt the latter view we shall probably espouse some theory of relativity and mathematize on the basis of existing data. If we adopt the former we shall look for hitherto unknown mass between the Earth and Mercury, and possibly a distribution of mass from the Sun outward, in some form other than that of planetary bodies. It might be that the mathematical treatment of the two problems thus antagonistically stated would be very nearly the same.

It is very far from the intention of the writer to discuss the problems of relativity, or to take sides for or against any relativity theory. The sole intention here is to point out as clearly as possible to the non-specialist that Mechanics, like Geometry, is an abstract and exact science, suitable for calculation; but that these calculations are applicable to nature only when two conditions are fulfilled,—first, no element of the problem is omitted from the calculations, and second, the measurements all are accurate. It is in last analysis impossible to know that these two conditions are met; consequently we ought under all circumstances, to exhaust all explanations which do not require a modification of a previously satisfactory abstract theory before we conclude that the theory, and not the observations and physical assumptions made before calculations are undertaken, is defective.

Having defined mass as an attribute of particles, Newton proceeded to present the laws of motion, including the laws of impact. In importance and generality these come first, and after them the inverse square law, not in its restricted form as applicable to universal gravitation, which may be a special case, but as applied to action at a distance generally.

Without any gravitational law whatever, the laws of impact suffice for the determination, to a first approximation, of the relative masses of colliding bodies. These, then, are essential. In dealing with the collisions of small bodies, the mass attractions are so small that they are unobservable in comparison with the results of collisions; and in dealing with the collisions of molecules in discussing the gas laws we ignore attractions and repulsions entirely, although eventually we may have to take into account local electrical attractions, in attaining satisfactory treatment of the behavior of gases.

Although the inverse square law is unnecessary for many purposes, and ought not to be used to define mass or its measure, it also is a universal law belonging to mechanics, and we shall apply it not only to gravitational attractions between masses, but also to electrical attractions and repulsions between positively and negatively charged parts of atoms. Newton's fame is more intimately associated with this law than with the impact laws which have been of greater practical use, and certainly of no less theoretical importance. But the inverse square law fascinates us because of its inclusiveness. When we discuss impact we discuss the behavior of each body, or particle taking part in a collision, usually only two bodies participating in one collision; but when we discuss gravity, or electrical attractions and repulsions, we must include every particle of matter, as the law requires that every particle of matter in existence shall have some influence upon the behavior of every other particle, although if the distance be great the influence may be small.

While the inverse square law of mass attractions between particles is purely mathematical, it can be applied only by measuring the motions of bodies composed of many particles,—vast numbers, in the cases of the planets, or the moon. The inverse square law supplied a relatively simple interpretation of Kepler's geometrical laws of planetary motion; but Newton did not rest his claim to universality of the mathematical law of inverse squares and mass attractions on planetary motions alone. He found a severer test and one that comes closer home to us in correlating the motion and the period of rotation of the moon around the earth at a known orbital distance with the acceleration of gravity of a falling body at the earth's surface; and it is said that he postponed the publication of the *Principia* for many years because the calculations based upon the supposed diameter of the Earth and the better known orbit of the Moon did not agree, publishing only after the Earth's diameter had been determined with sufficient accuracy to bring the calculations into agreement.

Although the beginnings of Mechanics as an absolute, mathematical and universal science are the work of Newton, and we should hold his gifts as well as the giver in reverence, we do not thereby detract from the credit of his great predecessors, especially Galileo, whose discoveries and theories prepared the minds of men for the mathematical treatment of celestial mechanics realized in the *Principia*.

The purpose of this discussion of Mathematics and Matter is not to decide whether Newton's conception is in complete accord with nature, but to point out the inherent difficulties which arise in the application of any mathematical theory, or ideal system, to nature, on an unlimited scale. These difficulties, as we have seen are of several kinds, some of which we can apprehend without great difficulty. The two kinds which are most clear are,—the impossibility of our making any measurement or comparison with absolute precision, except by counting, and the uncertainty as to our having taken into consideration all of the factors that should be considered, in a just application of any abstract theory we may have.

The unexplained discrepancies between theory and observation when we employ the Newtonian conceptions are appreciable in Mechanics, at the present time, only when we deal with problems involving great distances and large masses, like the problems involving peculiarities of the orbits of the inner planets. In the writers' investigation of spectra and atomic structure he will proceed upon the assumption that Newtonian Mechanics is applicable, at least for a first approximation, in dealing with the masses and dimensions of atoms and the parts of atoms. If there are discrepancies, they should be discoverable, like those in planetary orbits, by applying ordinary mechanics to these problems of atomic structure, and noting the failures to correspond. For this procedure it is of the utmost importance that we keep in mind the true nature of the conceptions we attempt to apply, and do not, either inadvertently or intentionally, depart therefrom, and subsequently, if our results are unsatisfactory, place the blame upon the Newtonian conceptions rather than upon the departures therefrom which we have introduced for our own convenience. The Newtonian conceptions, as the writer understands them, are:

Number. Precise counting proceeds by integers only. We have no warrant whatever for assuming that anything is divisible into absolutely equal parts, or the parts of anything capable of subdivision an indefinite number of times. The divisibility of any real thing depends upon the number of integers of which it is compounded. Even Arithmetic, therefore, has limited applications. Two half pianos do not necessarily make one complete piano.

Space is assumed to be abstract, in no way dependent upon time or matter. Therefore it does not, in definition or in mathematical use,

depend upon the flow of time, or the property of mass. When we consider it with relation to time, since time does not flow past it, we may properly call space eternal. In other words, there can be no short period of time when space is non-existent. When we consider space with reference to a particle, space has no attribute with which a particle can collide, nor can it attract a particle. This is another way of saying that space is devoid of mass. Space also is geometrically what we call Euclidean:—that is, unlike matter, which we do not regard as indefinitely divisible, but essentially discontinuous, space is absolutely continuous, and though not separable into units or fragments which may be rearranged, capable of being indefinitely subdivided dimensionally. We can take any unit of length that we please, in the investigation of geometrical problems, although in the application of geometry to practical problems we have to use units of such character as phenomena permit. The practical applications of geometry are limited by the discrete nature of matter, as well as by the limitations of our sense organs and measuring instruments.

Time is assumed to be abstract, in no way dependent upon measurement, or upon space or matter. Now is the same instant here on Earth as in Aldebaran. The time that is required to transmit a message from the Earth to the Sun has nothing to do with the distance. Light can traverse that distance in a few minutes, while a fast automobile running continuously on a smooth road would require several generations. Speed has nothing whatever to do with the conception of Now. The instant of time is universal and precise as well as abstract. It is completely independent of where, how far or how heavy.

Matter possesses an attribute not possessed in the slightest degree by space and time. This attribute is mass. The mass of a body is the sum of the masses of all of its particles, regardless of the motions of those particles with reference to other particles, to one another, or to absolute space. A body is a system of particles arranged in certain relationships to one another. A particle of matter is the ultimate unit with which mechanics deals. The attributes of particles can be defined only with respect to number, time and space, although matter is not thought of as derived from, or of the same nature as time or space.

If we think of a single particle in the simplest possible way, we conceive of it as now and motionless, in a certain place, and as we shall

see later, we are soon forced to ascribe to it some size, and as a consequence not only volume, but surface and shape. Thus our particle is considered only with reference to abstract space. We can think of a particle thus abstractly, even though we could not possibly obtain any sense perception of it without introducing other attributes.

We also can think of the particle as permanent. This introduces the time element. Then we can consider it as moving, or changing its position in space, even though we have no fixed reference points to define its position. Let us now introduce the idea number, by considering two particles instead of one. If both are motionless we can think of their distance apart—still abstractly, for we have no measure of distance to compare them with, as we have not defined the sizes of the particles themselves. By introducing one more particle we have three distances to consider instead of one, and relative motions and relative velocities may be conceived and compared. Thus the mechanical system may be built up, ideally, according to mathematical laws, without our knowing of any units of length, mass, time or other attributes by which we may apply the system to practical problems or to natural phenomena. These applied units, all of them, arise from our experiences in attempting to apply the ideal system. It may be that experience will some day be so complete that we can correlate our practical dimensions of length, mass, electrical charge, and the like with ideal dimensions of single particles, so that abstract mathematics and practical physics will present no discordances whatever. We have not as yet arrived anywhere near such a triumph. The “absolute, true and mathematical” science is still only ideal. Only in the ideal can any of our judgments be absolute, and in the ideal judgments are actually absolute, even though they may be in error. In experience with nature we never positively know two things or events to be absolutely alike in every attribute except one which renders them discrete, such as position; but we may know that they are so nearly alike that we cannot distinguish the one from the other except by position or some other single attribute.

CHAPTER II

MATHEMATICS AND RADIATION

Although certain branches of optics are of very ancient lineage, being closely related to the geometrical and astronomical sciences, there were no mathematical theories of a mechanical or even pseudo mechanical kind to account for light, worthy of mention, among the ancients. The prime requisite for any such theory was knowledge, or evidence, that light requires time to pass from place to place. The velocity of light is so high that the time taken for light to pass ordinary distances which are readily measured is too small to be observed with ordinary means. The first measurement of the velocity of light came after Galileo's invention of the telescope and the consequent discovery of the moons of Jupiter. These moons are eclipsed by the planet quite frequently, and the exact times these eclipses are observed by an astronomer, whose telescope must, of course, be located on Earth, are readily recordable. The first calculations of the velocity of light based upon such observations were made by Römer, in 1675. From observations taken at the time of year when the Earth was on the same side of the Sun as Jupiter, and observations taken when the Earth was on the opposite side of its orbit, Römer calculated that it takes 22 minutes for the light to cross the Earth's orbit, which gives a velocity of about 190,000 miles per second. Since then there have been found other means of measuring the velocity of light, and it is known that this velocity is practically constant in vacuum on Earth as well as in interplanetary space. It often is assumed to have uniform velocity throughout space, but this is an assumption that is bound up in theories with many other assumptions, and cannot be considered as verified by any experiment, in any absolute way. The same kind of considerations as those which suggest inaccuracy in the inverse square law of mass attractions over long distances may also be interpreted as indicating slight variations in the velocity of light in different parts of the universe, if we elect to ascribe irregularities to that velocity in order to avoid ascribing them elsewhere. However, under terrestrial conditions, in so far as we have been able to ascertain, the velocity of light in

vacuum is constant to within the probable error of our measurements thereof.

We will not review the history of the debate as to whether light should be regarded as due to vibrations or as corpuscular rays, the results of which cannot as yet be considered as completely satisfactory to the partizans of either side of the controversy. The wave theory required a suitable medium, and nobody was able to suggest a structure for such a medium and also to prove it sufficient to interpret all of the properties of the waves. Before the principal controversy raged, Newton conceived the possibility of an ether, such as a gas with particles so small that they could pass through the pores of ordinary solids with practically no obstruction; and he suggested that such a gas might explain the escape of heat from a body in a vacuum; but he did not consider such an ether capable of transmitting light as vibrations; nor could he regard light as a vibration for which he could enunciate mechanical laws; consequently he treated light, in his "Optick," which deals with such phenomena as reflection, refraction and diffraction, as corpuscular. For this he has been much blamed, and charged with responsibility for retarding progress of the undulatory theory, blame which the present writer considers entirely unmerited, for the particular form of undulatory theory which he opposed has gone by as completely as the corpuscular theory, being succeeded by the electromagnetic theory, which is a purely mathematical theory, without, as yet, any mechanical model to represent it. Newton could not accept the undulatory theory because neither he, nor anyone else in his day, was able to describe any medium in which undulations having the necessary properties could be transmitted. The only undulations ascribed to a perfect gas are, like sound, compression and rarification waves. Light waves were said to be transverse the wave front, like waves in a string; but this statement did not suffice for a complete and intelligible description, and no ideal model was ever successfully constructed showing the mechanical possibility of such motion in a medium through which solid bodies could pass without appreciable obstruction.

In the course of time Newton's corpuscular model, which was amenable to mathematical computation, was abandoned because it proved to be out of agreement with observed facts. But it was not replaced by a theory of transverse undulations based on any other

model, having an intelligible ether structure. The electromagnetic theory superseded it entirely, and this theory was based not primarily upon the phenomena of light, but upon the electrostatic and electromagnetic phenomena first extensively studied by Faraday.

Although there were many contributors to the theory of electricity and magnetism, many of whom developed limited parts of the theory and made special valuable applications, the formulation of general equations applicable to electromagnetic phenomena including light, as well as to electrical machinery, was the achievement of Maxwell, who was born more than a century after the death of Newton. According to the electromagnetic theory oscillations take place not like the motion of a particle on a string, but from one electrostatic state to another, accompanied by a transfer of energy from an electrostatic to an electromagnetic form and back again. There thus is another character to the vibration, which neither the old undulatory theory nor the corpuscular theory took into consideration. Neither a string, nor an ordinary gas, nor a solid, offers us the necessary concepts for a complete or operative model, for these do not require either electrical or magnetic properties for their conception. The electromagnetic properties which Maxwell interpreted as undergoing periodic transformations, and which could be used to explain light after accounting for electrical and magnetic phenomena of other kinds, eluded all of the mechanical ether models which were ever proposed, based upon analogies to states of matter in which the electrical structures of the individual atoms or the parts of atoms were not considered, if for no other reason, because they were not known at the times when such models were proposed.

But in spite of this elusive quality the mathematical theory of Maxwell was found applicable, with increasing success, to more and more practical electrical engineering problems. From a philosophical point of view, and perhaps also from a practical one as well, its most outstanding triumph came when Hertz found it completely satisfactory to interpret electromagnetic waves of much greater length than light waves, which he discovered, and which are now in common use in "radio" broadcasting. There is no conflict of any kind between the electromagnetic theory and ordinary mechanics. Both require the law known as "Conservation of Energy." They supplement one another. But the electromagnetic theory has never been derived from mathematical consideration of the possibilities of Newtonian

particles, either charged or uncharged electrically; nor has the Newtonian particle been shown to be, mathematically, a necessary consequence of Maxwell's equations.

That vibrations of any kind whatever require a medium seems obvious to most persons. Consequently most physicists, until very recently, have ascribed electromagnetic vibrations which traverse space to an all-pervading ether. Because in certain attributes at least light vibrations resemble transverse vibrations in strings and solids in being transverse to the wave front instead of normal thereto like sound vibrations in air, it was supposed that the ether could not be an ultra gas. Perhaps it may be shown that this is not a necessary conclusion, when the possibilities of structure of atoms of ether have been fully investigated mathematically. It may perhaps be shown that electromagnetic properties of the medium do not depend upon the fixity of the particles, as do the elastic properties of a solid, but rather on their extreme mobility. However this may be, and it is a matter for the solution of which we must look to the future, not to the past, Kelvin, whose influence was very great a generation ago, considered that the light transmitting properties of the ether, which he believed to be real, more closely resembled the elastic properties of a solid than the properties of any other known form of matter; and he regarded the ether as an immovable solid, which nevertheless yielded freely to permit the comparatively slow motion of the planets and other celestial bodies. Thus the idea became current that the ether might be like a solid matrix fixed in space, but capable of allowing massive motions through it without being dragged along thereby.

The writer well remembers hearing this view explained when he was in college, about the year 1890; and that to him, at least, the suggestion never seemed in the least satisfactory. Nevertheless it was very seriously considered, and is one of the theories that led to the present relativity theory which holds that there is no way in which the ether, if there be one, can be distinguished from space, experimentally. The famous Michelson-Morley experiment, suggested by Morley to Michelson, the inventor of the interferometer, and carried out jointly, was designed to test this hypothesis, and to measure the velocity of the Earth through the fixed ether, if the ether were found to be fixed in the sense suggested by Kelvin. The result of the tests was that the measurable effect, if real, did not exceed ten per cent of the amount expected if Kelvin's speculation were correct, and the ether at rest with respect to the Sun.

The smallness of the measured result, even if its absence were not thereby indicated, and the findings, such as they were, ascribable wholly to errors of various kinds, proved rather conclusively that such a model as a solid immovable ether would not suffice. There were two alternative explanations possible,—first, that the wrong kind of ether had been looked for, and that the ether, if real, must be more akin to an ideal gas than to an ideal solid, and second, that the effect sought for is immeasurable because its existence is impossible even theoretically. In case the first assumption is entertained we must consider the ether as circulating, more or less perfectly, with the motions of the Earth and other celestial bodies. We would not in that event expect the ether density to be absolutely the same throughout space, and any results from the Michelson Morley experiment might be small. This hypothesis would open the door to many interpretations of celestial phenomena quite different from the present ones. It would make ether distribution and circulation a matter to be investigated. The second assumption is of a more radical kind. By making the ether indistinguishable from space by any possible experiment, it makes the question of motion of ether in space meaningless. This second alternative has led to the theory of "Relativity," in which the Euclidean ideal of space is considered not in possible accord with nature, and not only is there no physical magnitude which may be taken as a standard independently of magnitudes of other kinds, but in the fundamental theory itself there is not even an ideal standard of reference possible, independent of all other ideal standards. In other words, to define anything in the Universe, or any attribute of anything in the universe, it is necessary to define it in connection with everything else in the universe, if our definition is to be precise. It is exactly the avoidance of such a situation that Newton sought when he defined his mathematical attributes space, time, particles, not with reference to one another, but as entirely independent of one another. It is absurd to suppose that Newton did this as an oversight. He did it purposely, with the intention of rendering his system absolute and mathematical. The only question left open for discussion was—Are his definitions true, in the sense of rendering possible a mathematical system that can be applied to nature with no greater error than is involved in our limited capacity for making precise counts and measurements.

The two seeming alternatives may possibly not be as irreconcilable

in final analysis as they seem to be in bald statement. A mathematical analysis of the results of a certain distribution and circulation of ether in space might, conceivably, give the same results as the mathematical consideration of the effects of gravitational fields in ether space. But we will not now concern ourselves with reconciliation. Instead of that we will note that the motions of ponderable bodies with which we have to deal are almost always so slight in comparison with the velocity of light that, in most practical problems we can ignore the discrepancies, even in those cases where, by theory, they might be pronounced appreciable.

In dealing with the transmission, reflection, refraction, diffraction and polarization of electromagnetic radiation we find the electromagnetic theory in such close accord with experiment that we may disregard discrepancies for all practical purposes. We apply this mathematical theory with satisfactory results, not only to ordinary optical phenomena, but to the design of apparatus for telegraphy, telephony, and for "wireless" broadcasting. It seems reasonable for us to expect that we may apply it also to the emission and the absorption of light and X-rays by matter in its various states of aggregation. But here we find that many eminent mathematical physicists raise the objection that experience acquired in dealing with objects perceived by our senses does not of itself justify our extending our geometrical and mechanical principles to very small objects such as atoms and parts of atoms any more than it does in extending them to the very large. In spite of this objection the writer will proceed by assuming that, even for the smallest appreciable bodies, the principles both of mechanics and of the electromagnetic theory may be applied legitimately, *for a first approximation*. If discrepancies are found, let us study them; but let us not abandon our general scheme, derived from so much experience in the ordinary fields, without most compelling reasons.

CHAPTER III

THE PROPERTIES OF CHEMICAL ELEMENTS

Many forms of matter are known by the character of the light they absorb readily, or emit when subjected to excitation, by heat, light or electric current. Most of the chapters of this book are devoted to discussion of the light so emitted or absorbed by the lighter elements, in chemically pure form; but before making any study of possible atomic structure from this point of view, it is very desirable that we prepare our minds by considering briefly some of the other data regarding atoms by which we might expect to obtain some enlightenment regarding atomic structure. For our specific purpose we will not attempt to trace the study of atoms back to their beginnings; but we will remind ourselves that Newton expressed the wish that he could trace the structure of all forms of matter to particles which mutually attract or repel one another, and "cohere in regular formations," because this idea is at the basis of the endeavors which are to follow in this work. Newton doubtless came to realize that knowledge of chemistry in his generation was inadequate for such an accomplishment, and consequently he devoted himself to problems for which solutions were, at least in part, possible at that time.

Newton considered matter as made up of particles which possess those essential attributes which we ascribe to solids. The liquid and the gaseous states were due to the separation of the particles to distances sufficient to permit their movement with respect to one another, without the loss of any essential attribute of the particles, to which the solid states are due. When the subdivision has been carried to a gaseous state we call the individual parts molecules, and consider them as discrete, moving with respect to one another according to the gas laws, colliding with one another, but not permanently cohering. By collisions sufficiently violent, or by the action of radiation upon them, molecules may be subdivided, and if the subdivision be carried far enough, may produce chemical atoms, which may encounter one another and recombine to form molecules different from those originally broken up. There are ninety-two species of chemical elements, according to our present knowledge,

and of these species several have varieties, called isotopes. We know that there are ninety-two related species because of the regular progression of their X-ray spectra. The lightest chemical atom is that of hydrogen; the heaviest that of uranium.

In Nature most of the chemical elements occur on Earth only in various solid or liquid states, for the most part combined with one another. At ordinary temperatures only the rare or "inert" gases, helium, neon, argon, krypton, xenon and radon occur as atoms uncombined with other atoms to form molecules or more complex structures, although at sufficiently low temperatures all of these may be liquified or solidified, showing that even these are not without attractions for one another. Other elements which occur naturally at terrestrial temperatures in the gaseous state have their atoms combined to form molecules, usually but not always with two atoms to the molecule, as in the usual forms of hydrogen, H_2 , oxygen, O_2 , nitrogen, N_2 . Most of the heavier elements, however, occur in the chemically pure condition at ordinary temperatures only as solids.

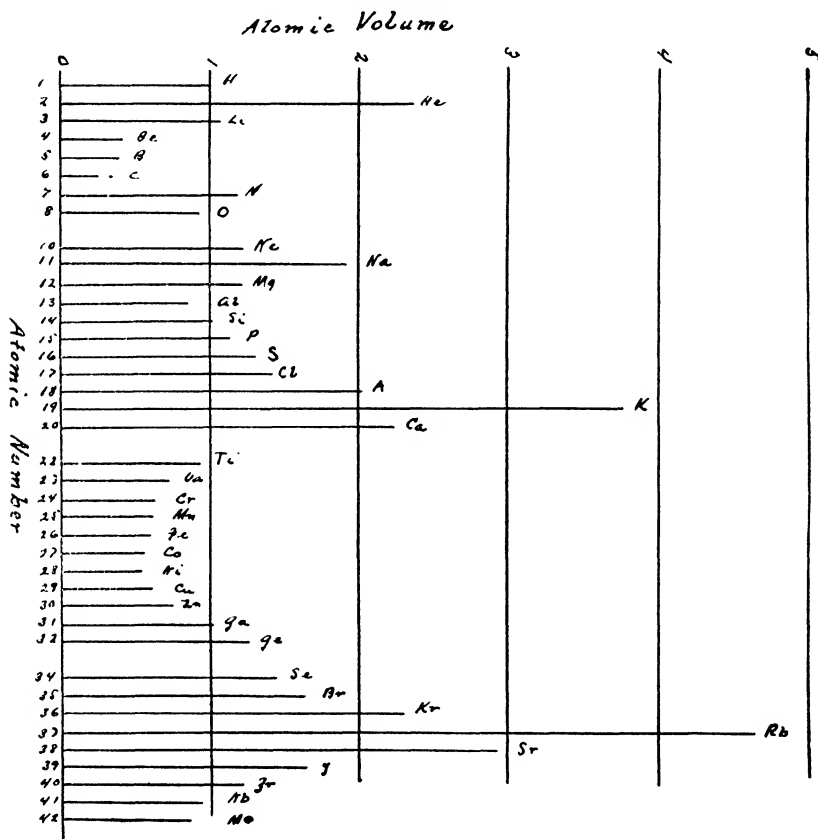
The atoms of various elements enter into countless combinations with one another, sometimes forming gas molecules, sometimes forming crystals, and often building up structures of very great complexity. Therefore it is simpler, for our purposes, for us to study the atoms in those combinations where only one kind are present in the structure,—that is, in the chemically pure states. It is very difficult to obtain any element in a pure state, and at present impossible to obtain some of the elements in that condition. Therefore many investigations which have been made are of limited value because the materials used in making them were not as pure as they should have been to justify fully the conclusions which might otherwise be drawn from the observations made. This is especially true of conclusions drawn from observations of spectra.

Since most elements can be obtained in approximately pure condition in solid or liquid states, by employing sufficiently low temperature, and since the volume and the weight of a given sample may both be measured with considerable precision, and since there are also means for determining the weight per atom with considerable precision, it is possible to find, with fair accuracy, the number of atoms in the sample taken, and therefore the volume required per atom in the solid or the liquid state at the temperature at which the volume is measured. This does not tell us the exact size or the shape

of any atom, but if all atomic volumes are determined in the same way it gives us at least some indication of the relative sizes of the atoms of the various chemical elements.

There are other properties of chemical atoms which may be determined by various means, and which serve for comparison of the elements with one another. Among these are atomic weight, melting point, boiling point, and chemical valence. For convenience these are set forth with atomic volumes (in terms of the atomic volume of hydrogen as unity) in Table 1, in which the elements are arranged in the order of atomic numbers, or X-ray spectra. The International atomic weights are given on the usual scale, in which $O = 16$. Examination of the table shows that when the elements are thus arranged there is a recurrence of somewhat similar properties at definite intervals. The atomic volume alternately decreases and increases, while the valence alternately increases and decreases. The atomic weights increase with increasing atomic number, except in a very few cases. The changes in melting points and boiling points are not as regular as the changes in other attributes, but they are distinctly periodic. Of all the properties which undergo periodic variation the atomic volumes seem to change with greatest regularity, but even in this attribute the change is not of the same regular character as the change in x-ray spectra upon which the atomic numbers are based. For greater convenience in comparison the atomic volumes of the first 42 elements are shown graphically in the accompanying chart. We shall have many occasions to refer to atomic volumes in the discussions which are to follow. As a preliminary let us consider only the two elements, hydrogen and helium. The atomic volume of helium is approximately two and one-third times as great as that of hydrogen. If we had nothing else to go by we might suspect that the helium atom contained two atoms of hydrogen and something more. If, without discarding this idea, we compare the atomic weights of these two elements, that of hydrogen being 1.008 and of helium 4, we would suspect that the weight of the other ingredient of helium is somewhat less than 2, and its size considerably less than that of a hydrogen atom. We might also suspect that the helium atom is chemically inert for the same kind of reason that the molecule H_2 is inert,—because of the mode of combination of its various parts; and that if these are respectively, positively and negatively charged, they are arranged in such a manner that they must be taken apart before another stable configuration may be formed.

If there be not good reasons for discarding such ideas as these, we might suspect that those atoms which have very large atomic volume contain several atoms of hydrogen, while those which have very small atomic volume contain no hydrogen atoms in their structure, and upon more searching study we might discover some



THE RELATIONSHIP OF ATOMIC VOLUME TO ATOMIC NUMBER

relationship between atomic volume and chemical properties, and perhaps also between atomic volume and spectra. In the interpretations of spectra to be given in subsequent chapters such relationships are pointed out very definitely. We shall not ignore the common properties of atoms, derived without knowledge of spectra, when we

discuss spectral lines, but on the contrary, the more readily a property is interpreted in terms employed in ordinary mechanics, the more reliance we shall place upon its use in interpreting spectra also.

Let us now consider in the briefest way certain obvious relationships between atomic volume and chemical valence. The lightest atom, hydrogen, which we will make use of in considering the properties of other atoms, as a standard of comparison whenever possible, has a chemical valence of one. Let us mean by this that one atom of hydrogen combines with one other atom of hydrogen to produce a stable molecule. An atom of helium will not combine with an atom of hydrogen, at least at ordinary temperatures and pressures, to form any stable compound. Ignoring altogether, for the present, whether helium will combine with anything else, we may say that, at ordinary temperatures the valence of helium, with respect to hydrogen, is 0. Any satisfactory scheme interpreting atomic structure must enlighten us as to why the helium atom does not combine with hydrogen, as well as why it is more than twice as large, but four times as heavy.

The next atom in the order of atomic numbers is lithium. It combines with one atom of hydrogen, and thus is said to possess the same valence as hydrogen,—the valence 1. The lithium atom has about the same volume as the hydrogen atom. From lithium to carbon the atomic volumes diminish, but the valences with respect to hydrogen increase from one to four. From carbon to neon the atomic volumes increase, while the valence with relation to hydrogen diminish, from four to zero. That there is a definite relationship between valence and size in this series is indubitable. Whether the volume is responsible for the valence, or the relationship is merely incidental will require investigation in connection with the study of atomic structure; but even at the outset of any such study we may note certain peculiarities,—two different atomic volumes are ascribed to carbon, one determined from graphite and the other from diamond, indicating either that there are two varieties of carbon atoms differing in structure, or that there are two different arrangements of the same kind of atoms, responsible for the different types of crystal structure. Another outstanding peculiarity is that the atomic volume of nitrogen is greater than that of oxygen, instead of less. The relationship between volume and valence is not a direct one, even in the first series of eight elements, with which our spectroscopic studies in the follow-

ing chapters of this book will, for the most part, be concerned. These departures from regularity, as well as the regularities, must be accounted for in any satisfactory theory of atomic structure.

Carbon has the smallest atomic volume of all the chemical elements. No chemical atom will combine singly with a greater number of hydrogen atoms than will carbon. Chemical valences greater than four assigned to any atom therefore do not indicate that the atom in question will combine with more hydrogen atoms, but that the valence greater than four is computed from combinations with other elements than hydrogen, usually with oxygen, taking the valence thereof as two because one oxygen atom combines with two hydrogen atoms.

If, as is almost always the case in inorganic chemistry and generally the case in organic chemistry where living organisms are not considered, it is possible to express the combination in terms of a definite formula giving the chemical constituents of each molecule of a substance,—such as CO_2 for carbon dioxide and H_2O for water,—the combining proportions are numerically definite, the chemical valence of each element may be expressed numerically, as an integer. If hydrogen is the sole criterion of valence, the expression H_2O implies that the numerical valence of oxygen is 2; while the expression CH_4 implies that the valence of carbon is 4. If we use these same valence numbers to interpret the combination CO_2 the requirements are satisfied, but if we did not start with the hydrogen valence as unity, we might explain CO_2 as due to a numerical valence of 2 in carbon and a valence of 1 in oxygen. The thing that is true is that in all such combinations the proportions are definite, but valence cannot be taken as an invariable attribute of any atom, regardless of the sizes and configurations of other atoms with which it may enter into combinations. Thus, in our general table of atomic properties there are several valence numbers given for many of the elements. When these numbers are large they do not mean that the atom in question will combine with as many hydrogen atoms as are represented by the valence number, but may mean that they will combine with half as many oxygen atoms as represented by the valence number, or something of a similar kind.

Since at intervals in the table arranged in order of atomic numbers there are chemical elements which enter into no chemical combinations at ordinary temperatures,—the “inert” gases,—we may divide

the long table into a number of chemical series, more or less regular, but not containing the same number of elements per series. This is done in Table 2, which is a mere subdivision of Table 1 into seven "series," the valence numbers being given in the first and the last columns. The principal valences increase from one to four and decrease regularly to zero; but the valences determined by other criteria may exceed four, and are somewhat erratic. We must seek in atomic structure reasons not only for the existence of chemical series, but also reasons for the number of terms in each series, and the place in each series where additional terms are introduced,—apparently interpolated; also reasons for the last series, containing radium, thorium and uranium being limited to so few members.

We now give our attention to a very brief consideration of those phenomena, other than optical and X-ray spectra which we will consider in much greater detail, which suggest that the chemical atoms are divisible into smaller units. These may be classified into two principal groups, to which may be added a third as the result of very recent researches. These groups are: (a) spontaneous emission of massive particles by certain elements, chiefly those of largest atomic number, (b) ejection of massive particles by certain elements, chiefly those of small atomic number as thus far reported, when bombarded by positive rays or other rapidly moving particles and (c) "cosmic rays" which enter the Earth's atmosphere from without, and are by some considered particles, charged or uncharged, and by others considered quanta of radiation.

Concerning the disintegration of heavy atoms, in spite of all that has been done to map out the process of disintegration of atoms, commencing with uranium or thorium and ending with isotopes of lead, the actual steps as outlined are largely hypothetical, though the presence of intermediate products appears certain. One fact attending the process, however, is completely established, and already put to many uses. This fact is that there are ejected by the radioactive elements numbers of positively charged ions, having a numerical ratio of mass to charge of two to one,—that is, if these particles have charge $+e$ their atomic weight is 2, or if they have charge $+2e$ their atomic weight is 4. This ratio of mass to charge or charge to mass has been determined by "positive ray analysis," which employs only well established principles of mechanics and the electromagnetic theory, and is quite independent of any assumptions concerning the

emission or the absorption of light. The steps ascribed to the disintegration of the heavy radioactive atoms have been based upon the assumption that these ions have mass 4 and not mass 2. The writer has not been able to find any evidence sufficient to convince him that this assumption is correct. He believes that the true mass of these "alpha" particles emitted by radium and other heavy elements is 2 and not 4, and that their charge is e and not $2e$. Reasons for this will be set forth in the discussion of the helium spectrum. The important fact to note is that particles of definite mass as well as definite charge are emitted, and that we are therefore justified in suspecting that they are contained in these atoms before their emission,—in other words that these atoms are composite.

It is equally certain that massive particles have been ejected from the lighter elements by bombardment of those elements by particles emitted by radium, and by other rapidly moving particles derived from other sources. Most of the work in this field is very recent and no attempt will be made to review it; but it seems certain that positive ions having a ratio of mass to charge of 2 to 1 have been produced from lithium as well as helium, and atoms of mass to charge ratio 1 from nitrogen. Very recently, also, neutral massive particles moving with very high velocities have been detected as one of the results of the bombardment of atoms by massive particles.

Thus it is seen that there are many indications that the atoms of many of the chemical elements are of composite structure; possibly separable into constituent parts each possessing definite mass of its own, in a manner akin to that in which chemical compounds may be separated into constituent atoms. It is suggested, by way of example, that what we call the helium atom, of mass 4, may be a combination of two hydrogen atoms, each of mass 1, and one sub-atom of smaller size of mass 2. The further suggestion easily follows,—that the sub-atom of mass 2 consists of an ion of mass 2 and charge $+e$, identical with the alpha particle, which usually is regarded as having mass 4 and charge $+2e$, and one electron. This suggestion, as thus far presented, has been raised in connection with the explanation of phenomena other than electromagnetic radiation, or light. It not only is legitimate, but incumbent upon us before we are willing to modify our mechanical and electromagnetic laws in the domain of light to inquire whether light may not be interpreted in accord with the conception that atoms are compounded of sub-atoms

before we assume that atoms are not divisible without permanent disintegration of the parts responsible for their essential attributes.

However, the simplest division to which an atom may be subjected does not involve appreciable loss of mass, but rather the separation of the atom into two parts,—one an electron possessing a negative charge $-e$ and very small mass, and the other an atomic ion possessing almost all of the mass of the atom and a charge of $+e$. Although further subdivision doubtless is possible, we have little or no evidence from positive ray analysis that atomic ions having normal atomic weights and charges greater than $+e$ are produced, although it is common in the prevailing theory of atomic structure to assume that many electrons might be separated from heavy atoms without any process of disintegration of the more massive part. This is very singular, for the reverse would be the natural expectation; and apparently this is supposed to be confirmed experimentally only in the case of helium and the alpha particle, for which another hypothesis is, at least, equally tenable, if spectroscopic evidence is not considered, and as will be shown later, much more tenable from a spectroscopic point of view on the basis of ordinary mechanics.

Before proceeding with our study of spectra it is necessary that brief reference be made to the subject of isotopes, especially as studied by methods of positive ray analysis. Most fortunately, the masses of charged particles, whether positively, or negatively charged, may be investigated by ballistic methods. As projectiles, all electrons behave alike, indicating that if their charges are equal, their masses also are equal, at least at equal velocities, in equal magnetic or electric fields. The positive ions, however, have different masses, and when the charges are known the masses may be determined by the ranges of the particles as projectiles, in known electric and magnetic fields. By such methods it has been found that ions derived from the same chemical elements have different masses, which leads us directly to one of two alternative conclusions,—either that the atoms themselves are of different masses prior to ionization, and the element is isotopic, there being several varieties of structure classified as the same element, or that the atoms are divisible, the several parts subject to recombination, the ions which give different masses being due to different recombinations of component parts. Both suppositions are in keeping with the hypothesis that atoms are divisible, and both may be true. In Table 3 are given the ionic masses as-

cribed to the various elements by Aston, in his book on isotopes. It scarcely seems likely that as many different weights as assigned to mercury could be attributable to differences in a single nuclear structure, while other elements have but one variety of nucleus. On the other hand, if the element is compound, and possesses several nuclei of different masses, not only several varieties having the same chemical properties may be possible, but it also is possible that there are a few true isotopes of mercury possessing like chemical properties, and a large number of possible recombinations of atoms that have been partially broken, which make the number of positive ions of different masses greater than the number of true chemical isotopes.

CHAPTER IV

EMISSION AND ABSORPTION OF LIGHT

In our chapter on the Electromagnetic Theory we have already noted that the emission and the absorption of long ether waves by the apparatus used in "wireless" broadcasting and reception follow the mathematical rules of the electromagnetic theory. In emitting such waves, currents of electricity comprising immense numbers of electrons surge back and forth along conductors of considerable length. The frequencies of the broadcast waves are fixed by the length, the inductance and the capacity of the circuit, and may be calculated by the radio engineer before he designs his circuits.

That radiation which we call light is transmitted as electromagnetic waves at the same velocity as the radio waves of wireless telegraphy; but it is not emitted by apparatus of the same, or even of a similar kind. In the case of an excited gas, the emitting bodies are molecules, atoms or parts of atoms, in each of which a very few electrons at the utmost can take part. The ordinary effects of capacity observable in circuits carrying very large numbers of electrons, and due in part at least to crowding electrons closer together at one period of the oscillation than at another, can scarcely apply in the emission of light. Yet it still must be regarded as possible that light radiations originate with the movement of electrons, after displacement from normal, or stable positions in any material, during their return to the same normal positions, or to other positions of stability.

In this chapter we shall use the word light in referring to any radiation emitted or absorbed by material in a natural state,—that is, by molecules, atoms or parts of atoms, or coöperative units or groups of atoms, or by electrons in any such structures. Thus we include not only visible light but also infra red and ultraviolet radiations as well as X-rays, but we exclude for convenience radiations of long wave length set up by mechanisms of human contrivance, such as used in wireless signaling. This distinction between light and other electromagnetic radiations is made for convenience, to avoid any assumptions whatever as to the mechanism by which light is emitted and absorbed, and not for the purpose of justifying any assumptions

that light and other electromagnetic radiations differ in any essential respect other than the obvious one of frequency of vibration.

The kind of light with which our ordinary experience renders us most familiar is that emitted by bodies as a result of high temperature. The light from the Sun and the light from the filament of an incandescent lamp are both examples of such light, though the emitting bodies are very different. It is found by experience and experiment that when light from any hot body is spread out into a spectrum by refraction or diffraction, it produces a continuous spectrum, which may be more or less modified by the character of the surface of the emitting body or the structure of the gases or other material through which the light passes after emission. But if suitable precautions be taken to eliminate disturbing effects due to differences in temperature in the emitting layers of matter close to the radiating body, and to absorption, it is found that continuous spectra emitted as a result of temperature only, are all very nearly, if not exactly alike for any given temperature, regardless of the chemical structure of the emitting substance. The total amount of energy radiated from a given surface in a given direction is proportional, at least approximately, to the fourth power of the absolute temperature. The maximum frequency of radiation emitted by a hot body is also determined by the temperature, as is also the distribution of the energy throughout the entire continuous spectrum. In other words, regardless of the chemical structure of a body radiating as a result of temperature only,—giving out what is called “black body” radiation,—the temperature alone fixes the maximum frequency, the distribution of energy in the spectrum, and the intensity of radiation per unit of surface, and consequently, the total radiation energy per second for a body of given size and shape.

With observation proclaiming such a rule (subject only, so far as we know, to such discrepancies as seem likely to be due to experimental errors), it is natural for the mathematical physicist to seek an explanation with reference to some universal attribute of matter, not dependent upon atomic structure, in which atoms obviously differ, or else with reference to some universal attribute of radiation, as radiation, and independent of the structure of matter.

Various mathematicians have made intensive studies of this problem, seeking to interpret the observed facts by application of thermodynamic and probability laws to various assumptions, or postulates.

None of these studies have resulted in mathematical systems that are wholly in accord with experiment, as they should be if the assumptions as well as the mathematical developments were entirely correct, and inclusive of all factors which actually enter into the problem. The assumptions made by Planck, which gave results more nearly in conformity with observation than any others yet tried, ascribed the universal attribute responsible for black body radiation to the nature of radiation rather than to the structure of matter; or at least it seems that he did so to the present writer, and in this manner his work is usually presented to the student. Planck considered black body radiation as made up exclusively of small units of energy, which he termed "quanta." Each quantum consisted of strictly "monochromatic" radiation, and a definite quantity of energy, equal to the frequency multiplied by a constant, which he designated by the letter h . By applying certain principles of probability and thermodynamic laws very like those applied to the consideration of collisions of molecules in gases, Planck was able to account mathematically, if not philosophically, for the observed distribution of energy in black body spectra, to within a few percent. But there was no warrant for assuming radiation quanta of equal energy, or that, if there be such quanta, they are monochromatic, other than the fact that Planck's calculations give energy distribution curves somewhat more in accord with observed energy distribution curves than were obtained by the calculations of others, who did not employ his hypothesis. Even if the idea of quanta be assumed, there is no necessity for assuming monochromatism; in fact it evidently might be possible that some other assumption might give results that would be in better accord with experiment. There is in the black body spectrum no observed discontinuity. In so far as the black body is concerned, Planck's assumption is a mathematical convenience, and nothing more. If there is physical evidence of individual quanta we must seek it in connection with records of some other kind of physical phenomena.

Continuous spectra may be excited not only by heat, but also by light or X-rays falling upon matter in any state of aggregation; also by electric currents flowing through the material. As in case of black body radiation, where, as we have seen, the temperature fixes the maximum frequency of the excited radiation, so when light is the exciting cause of other light, some of the light emitted by the second-

any source gives a continuous spectrum, the highest frequency of which may equal, but not exceed, the highest frequency of the exciting light. Similarly, if electric current is the exciting source of energy, the maximum frequency of the continuous spectrum excited thereby is proportional to the exciting voltage. We may therefore state with confidence one general rule that applies to the continuous spectra excited in various ways. The highest frequency of a continuous spectrum excited in any form of matter is independent of the chemical state of aggregation of the matter, and is fixed by the character of the excitation. If heat is the exciting cause, the highest frequency is fixed by the temperature; if light is the exciting cause, the highest frequency is fixed by the frequency of the exciting light; if electric current is the exciting cause, the highest frequency is fixed by the highest exciting voltage.

We now are prepared to consider the conditions necessary for the excitation of radiation which does not give continuous spectra. The observable discontinuities in spectra are manifested as spectral lines, or bands. These occur as distinct bright lines or bars in the spectra, known as emission lines, superposed upon a non-luminous background or upon a less luminous background of continuous character, or as dark lines upon a continuous spectrum as a background. Regardless of whether or not we are able to interpret the structure of matter from observations of these lines, there can be no question whatever as to the fact that spectral lines, whether emission or absorption lines, indicate the presence of certain specific forms of matter in the emitting substances or the absorbing media. In the case of solar light the bright continuous spectrum is like black body radiation, produced by high temperature in any form of matter regardless of chemical structure, and does not reveal the chemical structure of the elements in the Sun. The dark Fraunhofer lines, on the contrary, are due to absorption of parts of the solar radiation by the specific forms of matter, including many with which we are familiar on Earth, in the solar atmosphere, in various states of aggregation and disruption.

Spectral lines may be excited by radiation, or by electric currents passing through gases, in addition to continuous spectra; but seldom, perhaps never, in the absence of continuous spectra, although the accompanying continuous spectra quite frequently have their greatest intensity in a region of higher frequencies than the lines which

accompany them. However, the rule that the maximum frequency due to a given excitation cannot exceed a certain limit applies to spectral lines as well as to continuous spectra.

In most discussions of the excitation of spectra it is assumed that line spectra are excited directly, by incident light, or electron impact. The present writer believes that there are many reasons for thinking that light and electron impact excite, as a general if not a universal rule, non-characteristic or continuous spectra, and that the line spectra are as a general rule excited in their turn by the non-characteristic spectra, and not by direct electron impact, or the immediate absorption of incident light by molecules or atoms. Reasons for this thought will appear during the discussions to follow. Be this as it may, if the characteristic spectra originate in specific forms of matter, they should, if properly interpreted, reveal to us something about the structures of those forms of matter in which they originate. The writer's interpretation of the spectra of the lighter elements, based entirely upon Newtonian Mechanics, and the electromagnetic theory, is given in the subsequent chapters. This interpretation does not require a priori interpretation of the structure of all matter, giving reasons for the proportionality of excitation voltage and maximum frequency of resultant light, which, in the writer's opinion, is a matter to be studied successfully only after the grosser subject of atomic structure has been brought into harmony with mechanics, not before. But since 1912 almost all researches dealing with spectra and allied subjects have been published as interpretive or demonstrative of some phase of the "quantum theory," and not in terms of Newtonian mechanics.

It is necessary for the writer to use the data so published. Therefore, to avoid possible misconceptions on the part of the reader, it seems necessary to state in this connection the assumptions that are commonly made in interpreting spectra, especially spectral lines, which the present writer does not make. We have already noted Planck's assumption of quanta, each quantum having the energy $h\nu = w$, where w is the total energy of the quantum, ν its frequency and h a universal constant. It was assumed by Einstein, Bohr and others that if an electron moving with kinetic energy w encounters matter in the most favorable manner it can come to complete rest, and convert all of its energy into radiation at the frequency ν . An electron can be given acceleration by "falling" through a potential

difference, or voltage. Thus, if v is the voltage, $w = ev$ is the energy acquired by an electron of charge e falling through a voltage v . Combining this with the assumption as to the energy of a quantum we have $w = h\nu = ev$ in case of a "perfect" collision. But if the collision is imperfect all of the energy of the electron, according to the theory, will not be converted into radiation. Part of the energy will still be kinetic energy of the electron. We will represent this by w' . Then according to the quantum theory the energy converted into radiation will be a quantum of less frequency, represented by $w - w' = h\nu$.

Accepting these energy equations, which the writer does not accept, at least as *a priori* postulates, Bohr used them to interpret the primary spectrum of hydrogen, publishing his first paper along these lines in 1912, and subsequently extending his assumptions to other spectra by various supplementary assumptions and postulates. But in order to use these energy equations Bohr adopted other assumptions as well. Of the other assumptions adopted in the case of hydrogen the most important, of all was this: All of the quanta of radiation that combine to produce the lines of the primary spectrum of hydrogen are emitted by single atoms. This assumption does not need to be made in order to explain the lines in accordance with ordinary mechanical principles, and consequently I do not make it. It is not something that has been found out by experiment,—in fact, all of the evidence seems to the present writer to be against it; but it is an assumption that renders it impossible to explain line spectra in conformity with mechanical principles and the electromagnetic theory, and therefore it demanded other postulates to interpret atomic structure.

As the writer does not agree with this fundamental assumption about the origin of spectral lines, but has a conception which he believes better, and which does not require postulates unacceptable to mechanical or electromagnetic theory to sustain it, obviously no useful purpose could be served by the writer indulging in any discussion of other postulates of the quantum theory or its heirs or assigns, which all adhere to this fundamental assumption which has been rejected.

If Bohr's theory of atomic structure rests upon an assumption as to the origin of spectra, and the quantum theory rests upon Bohr's interpretation of atomic structure, the quantum theory must be discarded as insecurely founded. But there are many who believe

that the theory of quanta is so firmly established on other evidence that the evidence for Bohr's atom is derived from the quantum theory, rather than the reverse. Those who hold this view are influenced largely by the fact that X-rays not only excite radiation, but also cause the expulsion of electrons from matter upon which they fall, the electrons being expelled with kinetic energy given by the equation $ev = h\nu$. They argue that this energy ev , which leaves the body as kinetic energy with the expelled electron, requires the receipt of an equal quantity of energy $h\nu$, as a single unit. Otherwise, they argue, the material upon which the X-rays fall would have to gather up radiation energy over a large surface, involving perhaps millions of atoms, and concentrate it upon the individual electron expelled. In the writer's opinion this argument, even if the reasoning be true, carries no weight. It is quite as difficult to conceive a mechanism by which a quantum of radiant energy could have so small a front as to single out one electron for impact, and to expend all its energy like a billiard shot on a single ball in a pack that has not been broken, as it is to consider energy as gathered up by an aggregation of atoms, and ultimately single electrons, here and there, expelled with appropriate maximum energy proportional to maximum radiation frequency. The difficulty escaped by the quantum theory certainly is no greater than the difficulty introduced by it, even if we disregard the more serious matter of abrogation of the electromagnetic theory which the theory requires.

The electromagnetic theory treats radiation arising from molecules and atoms in the same manner as it treats "radio" waves,—as waves in a medium,—waves with extended front, weakening in intensity per unit of area of wave front, according to the geometrical inverse square law. It postulates nothing about the source,—whether the waves originate as monochromatic vibrations in a single source unit or whether monochromatic waves are derived from more than one original source. It has nothing to say as to whether, at their origins the wave chains be long or short. For answers to these questions the electromagnetic theory refers us to experimental study, not to arguments based upon a priori considerations to be spun out of the theory itself.

We may approach the investigation of this subject by considering the excitation of light as possibly analogous to the excitation of waves used in wireless telegraphy. In that art the waves are set up by os-

cillating discharges, possess the frequencies of the oscillations, and the intensities determined by the excitation. Moreover, the single oscillatory discharge broadcasts in all directions, and the wave intensity diminishes in accordance with electromagnetic laws. Successive discharges produce successive groups of impulses, but there appears to be no confinement of any group of impulses to a single direction. Unless we desire to consider light as something different in kind, we cannot otherwise than surmise that atoms and molecules, in the process of emitting light, also act intermittently,—that there is some initial disturbance, which we call excitation, followed by a return to normal, during which radiation takes place, at the frequencies of the motions of the electrons which are in process of return to stability.

A definite disturbance and rearrangement in an atom or a molecule,—such as a chemical reaction would imply, would of course require energy to break up a given configuration, and after the breaking up had taken place, energy would be liberated by the formation of a new stable configuration. For any specific change in structure, whether a chemical change in the ordinary sense of the word or a physical change of some other kind within the structure, a definite amount of energy for each unit produced by the change would be liberated. This unit of energy might be called a chemical quantum, characteristic of the reaction; and there might be cases where such energy would be liberated, in the form of radiation. In such a sense there can be no doubt that radiation may be emitted, or absorbed in quanta, which is only to say that physical or chemical changes require definite amounts of radiation energy to initiate them, and release definite amounts of energy in attaining stability.

If the energy units liberated by such changes, in the form of radiation, are due to to-and-fro oscillation of charged particles (electrons or ions), they would be expected to be electromagnetic in character, and to radiate, like the broadcasting disturbances, at the natural frequency or frequencies of the oscillation occasioning them. We should seek explanation of their frequencies in the structures of the atoms or molecules from which they arise. We should also be very cautious in ascribing sources, for since in a gas, radiation from any one atom or molecule would have to pass other atoms and molecules, the original form of radiation “quanta” might be greatly altered by absorption and accretion before reaching the eye or the photographic

plate, or other optical appliances which are used by us to resolve or to record the light. In other words, what may appear to us to be monochromatic light, in the form of a spectral line, may be altogether a secondary result, originating not in one molecule or atom, but resulting from the coöperative action of two, or many sources.

Radiation quanta in the sense outlined above, meaning units of radiation caused by definite physical changes in or between atoms or molecules are quite acceptable to ordinary mechanics. They are not of necessity, on a priori grounds, monochromatic. It will be our duty later to inquire what the nature of such radiations should be, according to ordinary mechanical principles, and to investigate spectra from this point of view. Such quanta, however, are not what are designated as "quanta" in the current theories of spectra and atomic structure. The popular theories postulate not merely that a change within an atom releases a certain amount of energy, but also that the energy so liberated is monochromatic, and that it moves as a unit in one direction only, like a particle, and does not spread out in all directions on a broad wave front, like ordinary electrical disturbances with which engineers are familiar. According to the quantum theory the spreading of radiation in different directions is due to there being very many quanta, each pursuing its own direction, and moving, in the main, rectilinearly.

In proceeding with the discussion of atomic structure by the interpretation of spectra the writer will utilize all of the information available as to the correlation and classification of spectral lines, and as to the mathematical rules of such classifications, with a mind thankful for what has been accomplished and rendered available, quite regardless of interpretations of the data with which he may not be in agreement. But in his own interpretation he will not consciously introduce any mathematical or pseudophysical postulates contrary to the implications of mechanics and the electromagnetic theory.

CHAPTER V

IDEAL ATOMS AND IDEAL SPECTRA

As briefly outlined in preceding chapters, the Quantum Theory of atomic structure, founded by Bohr in 1912, began with a tacit assumption that all of the lines of the primary spectrum of hydrogen originate in monochromatic quanta emitted by hydrogen atoms. Bohr proceeded to invent an atomic structure which would be compatible with this assumption, and in doing so he was constrained to depart from the principles of mechanics and of the electromagnetic theory, as previously understood and as used in dealing with engineering problems.

We will approach the problem in quite a different manner. We will assume that the Newtonian conception of particles is applicable, and that atoms are built of particles; and we will therefore inquire what types of spectra are to be expected from ideal atoms of a Newtonian kind; and then we will inquire whether there are any actual spectra that resemble the ideal spectra to be anticipated according to Newtonian theory,—supplemented, of course, by our later acquired knowledge of the electrical properties of particles.

Such ideal atoms should possess the properties of ordinary solids, such as size, shape, mass, elasticity. Their parts also may be electrically charged. We shall not, however, at the outset, make assumptions about the structure of atoms, such as that all of the mass is concentrated at the nucleus, and that the space designated as the atomic volume is practically empty. Such assumptions were introduced by Rutherford, with his model of the planetary atom, amplified by Bohr. But while not asserting the atom to be void of mass in most of the space assigned to the atomic volume, we accept the experiments which led Rutherford to that conjecture. The experiments prove that very rapidly moving particles,—both electrons and positively charged ions,—may be projected through atoms if given sufficiently high velocities. We realize that the atomic structure permits this, whatever it may be; but there may be possible, theoretically, more than one kind of structure which would permit this, and we have no special warrant to select the one which requires a

vacuum within the atom in preference to any other, on merely arbitrary a priori grounds. But we shall insist that atoms, as wholes, when moving with moderate velocities, are capable of colliding with one another and rebounding, and may for many purposes be thought of as possessing the ordinary attributes of elastic solids. As for the structure from the nuclear center outward, we leave it for future investigations, and refrain from prejudicing this matter by postulates.

Since we start in total ignorance as to what the shape of an atom may be, in order to form some idea as to what to expect if size and shape are important factors in the production of spectra, let us assume a very simple, purely ideal case. Let us suppose we have ions, all alike, each spherical in shape, with a charge of $+e$ concentrated at the center; and for each such ion we have a spherical electron, of charge $-e$, of mass very many times smaller than the mass of the ion, and of diameter so small as to be practically negligible in comparison with the diameter of the ion. We will not postulate anything more as to the internal structure of either ion or electron, but will assume that they attract one another according to the inverse square law, as if the charges were concentrated at the centers of figure, and that, for impacts at moderate velocities, they behave upon collision as perfectly elastic solid bodies. These suppositions apply to our model. We are not postulating that they apply absolutely to real atoms, but we expect to make inquiry as to whether, in actual observed spectra, we find anything like what we should expect, if any real atoms behave to some extent, as our ideal atom ought to behave, under strictly mechanical laws such as are used in ordinary engineering.

Consider a system comprising one such ion and one electron. Suppose the electron to be at rest, in surface contact with the ion. Let R be the radius of the ion, from its center to the center of the electron. The attraction between the ion and the electron is $F = \frac{e^2}{R^2}$ and the work required to separate the two is $W = \frac{e^2}{R}$. The force F is resisted by contact pressure at the surface. The ion being elastic there is, of course, some deflection, but if the electron be removed the ion will return to its truly spherical shape. If the electron be dropped from some distance above the surface it will rebound to an equal distance, again fall and rebound, and continue to bounce until the energy

represented by the separation is dissipated. If there be no medium in which the bouncing takes place, other than space as defined by Newton, the oscillating or bouncing motion will be perpetual. There would under these circumstances be three factors which coöperate to determine the frequency of the oscillations,—the height of the drop, or the amplitude of the oscillation, the rigidity of the surface, or the rate at which it arrests the impact of the electron, and the mass of the electron. If, however, this system be placed in any medium capable of absorbing energy, the frequency of the oscillations will become greater as the amplitude becomes less, and the frequency will reach an upper limit as the amplitude becomes zero. The motion will be similar to that of a rubber ball bouncing upon a hard pavement. If the medium be of such character that it can radiate the energy which it absorbs,—in other words, if it be electromagnetic, as the ether is supposed to be by those who believe that there is an ether,—the frequency of the radiations will be the same as the frequency of the oscillations of the electron.

For convenience we will designate frequencies by ν , and the limiting frequency of the system by N . N does not depend upon the excitation, or the amount of separation before bouncing sets in, but only upon the dimension R , the hardness of the surfaces, and the charges and masses. In other words, N is a number characteristic of the atom, and represents the highest frequency characteristic of the system. We may if we desire express the frequency N by the equation $N = kF$, where k is a constant characteristic of the ion under consideration. The spectrum emitted by our theoretical atom in the process of acquiring stability after the electron has been disturbed is a continuous spectrum, the initial frequency of which depends upon the displacement, and is less than N , while the final frequency, at which radiation ceases, is always N . The amount of radiation radiated per oscillation diminishes as N is approached. The variation of energy radiated as the frequency increases is a matter which we are not at present prepared to consider, and which we do not need to know at the present stage of our inquiry.

Let us suppose that we had a system consisting of very many atoms of the character just outlined, all exactly alike, subjected to excitation, by the passage of current or otherwise, which we need not now consider, but in such a manner that the various atoms are unequally excited. Let us assume that some of them are only very slightly

disturbed, while others are so acted on as to be deprived of their electrons altogether. Let us ignore considerations of what might happen as a result of combinations taking place between the atoms, and consider only what we should expect as the character of the spectrum due to the joint action of the many atoms. Obviously, according to ordinary principles of mechanics, the spectrum would be a composite of the spectra of the individual atoms. It would have an upper limit at N , and the lower limit would be the frequency of the most highly excited, or in this case ionized, atom, which is zero. The mean distribution of the intensities would depend upon the distribution of the excitation among the various atoms. This would depend upon the exciting voltage, the current density, the gas density, and perhaps upon many other factors, especially the purity of the gas, its state of aggregation and like matters. If the voltage were less than the ionization potential so that none of the atoms could be ionized, the continuous spectrum would not reach zero with its lower limit; but it always would reach, and terminate, at the upper limit N .

There are very many continuous spectra with definite upper frequency limits known to the spectroscopist. The simplest example, and one that fits our ideal atom most admirably, is that element of the continuous spectrum of hydrogen which accompanies the primary spectrum, the limit of which is most easily observed when the secondary spectrum is absent. The frequency limit of this spectrum is $N = 109678$. This is called the Rydberg Number for hydrogen. This frequency is in the ultraviolet, or Schumann region, and of such character as not to be transmitted through glass. It is not seen, nor is it recorded on photographic plates recording the Balmer lines, in air, the study of which is usually conducted without reference to the continuous spectrum which accompanies them at their genesis.

Our model is thus seen capable of explaining, to some extent, continuous spectra, which for the most part are either altogether neglected by the popular theories, or altogether ignored. But thus far it does not account for spectral lines; and while spectral lines contain but a part, often but a small part, of the energy emitted by an excited gas, the continuous spectra carrying in most cases if not in all a much larger portion, it is indeed necessary to account for the lines; and it is upon the lines that we must rely for the most part for measurements of sufficient accuracy for mathematical analyses. Let us therefore investigate what kinds of spectra we should expect from

combinations of atoms, of the very simple kind represented by our ideal model.

Let Figure 1 represent the single atom which we have been discussing. Figures 2 and 3 then represent the simplest possible forms of molecules possessing two and three atoms respectively. In these forms the atoms are shown with their electronic and ionic centers all in the same straight line, and their surfaces in contact. Demonstration that these configurations are inherently stable if undisturbed from without is so simple a matter that we need not give space to it here. The middle electron in Figure 2 is attracted equally by each of the ions, which repel one another. The terminal electron, however, repels the middle electron with a force $\frac{e^2}{(2R)^2}$ or one fourth the force which holds the terminal electron to the single atom illustrated by Figure 1. The frequency limit of the middle electron in Figure 2 therefore is one fourth that of the single atom; and similarly, the

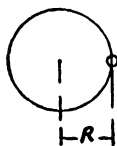


FIG. 1

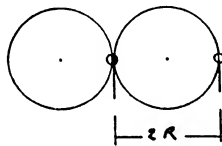


FIG. 2

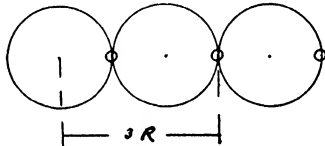


FIG. 3

frequency limit of the middle electron in the molecule having three atoms is one ninth that of the single atom.

We may liken these systems to the gravity systems of a pendulum supported at different distances from the Earth. The frequency depends only upon the gravitational constant of the Earth, and the distance out, as long as the length of the pendulum is constant. The frequency is directly proportional to the inverse square of the distance. In the case of the spherical atoms we have been considering, the distance is, in every case, an integral multiple of the atomic radius. We need not know the exact nature of the support, to apply the law; all that we need to know in these simple cases to obtain the frequency limit of any line molecule is the number of molecules in the line.

It is obvious that the molecules illustrated in Figures 2 and 3 would, upon moderate excitation, give rise to continuous spectra

with their limits definitely fixed; but it also is obvious that violent excitation would also tend to spread the atoms apart, and that when the spread were sufficient dissociation would result; in other words, there would be two atoms instead of one molecule. We could not expect the continuous spectrum resulting from large numbers of such molecules to resemble the continuous spectrum of the atoms very closely, in the matter of energy distribution at the various frequencies, though it would resemble it in the matter of possessing a definite upper limit. These continuous spectra due to line molecules, however, would be overlapped by one another and by the continuous spectra due to atoms, and it might be difficult to ascertain their limits exactly on that account.

It is obvious that mere integration of the results of radiation taking place from number of molecules such as have been discussed could not result in spectral lines. If such bodies are to produce lines, or elements of which lines are composed, they must coöperate with one another in some other way. The most obvious way in which co-operation might occur is by the absorption of energy emitted by one atom or molecule by other atoms or molecules, and the consequent modification of the energy which is not wholly absorbed. Let us consider this possibility.

THE SIMPLEST PRODUCTION OF A SPECTRAL LINE

Let us suppose one of our theoretical atoms to have been excited in such a manner as to remove its electron to a considerable distance, and that the electron is returning to stability by a series of bounces, accompanied by radiation of a continuous spectrum. Let curve *a* in Figure 4 represent qualitatively the relationship between frequency and time, during the return to normal. The final frequency, or frequency limit is N . Suppose that some of this radiation is passing a molecule composed of two such atoms, as in Figure 2, the frequency limit of which is $N \div 4$. As long as the radiation from the atom passing the molecule has a frequency less than $N \div 4$ the electron within the molecule cannot be appreciably disturbed by it; but when the radiation has a frequency equal to $N \div 4$ the molecule will absorb some of it, and begin to separate. It also will act as a radiation center for the energy it has absorbed, but at its own frequency. It will not cease absorbing, and consequently will not cease radiating until it ceases to receive energy from the atom. A necessary con-

sequence of this, if there were only one atom and one molecule in the system, would be that the two would cease radiating at almost the same instant,—or their radiation energies would fade out at the same time. Just before the radiation ceased, the atom would be radiating at frequency N and the molecule at frequency $N \div 4$. If it be possible to create difference frequencies in radiation, as it is possible to create difference tones in music, we should expect a difference frequency in the light passing the molecule of frequency $N (1 - \frac{1}{4})$. It is clear from Figure 4 that the curve *a* representing the frequency to time relationship for the atom and the curve *b* representing the same relationship for the molecule, must approach parallelism for an appreciable interval of time (indicated by t on the diagram) just before rest is attained; and it also is clear that the longer this period

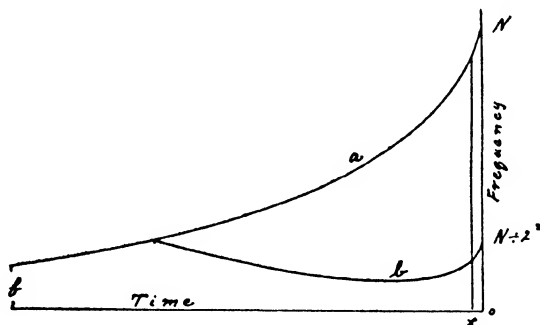


FIG. 4

of parallelism, the greater interval during which the difference frequency will be substantially monochromatic. If the difference were absolutely constant for an appreciable interval, the line would be absolutely monochromatic during that interval; but if the difference approached uniformity we would have a line element which, while not absolutely monochromatic, would be approximately so. If the difference departed more from uniformity we might have not a sharp line but a bar, or broadened line, or short continuous spectrum without either of its limits sharply defined.

Similarly, coöperation of the atom, Figure 1 and the molecule containing 3 atoms, Figure 3, could produce a line of frequency $N \left(1 - \frac{1}{3^2}\right)$, and coöperation of the molecules illustrated in Figures 2 and 3 could produce a line of frequency $N \left(\frac{1}{2^2} - \frac{1}{3^2}\right)$.

This discussion and the figures used for rendering it readily understandable are qualitative only. It is not intended to indicate the actual relationships between frequency and radiation, or the relative duration of the period of approximate monochromatism of the line, but only the possibility of producing approximately monochromatic lines by the coöperation of sources neither of which is even approximately monochromatic. For purposes of simplicity we assumed the presence of only one atom and one molecule acting at one time, though it is obvious that any radiating atom might stimulate numerous molecules in various directions, and different distances from it; also that any molecule might absorb energy from a variety of sources at various distances and directions from it. It is obvious that where the atoms and the molecules were closely crowded together there would be less opportunity for any of them to become altogether quiescent, so that the lines would be expected to become broadened by high gas pressure, and intensive discharge (high current density or condensed discharge).

One assumption should be commented upon. It has been assumed that an atom or a molecule does not become excited (in the sense of having its electron or electrons set into vibration) by light of less frequency than the natural frequency limit of the electrons within the molecule. The writer is content to have this considered an **assumption**, so far as his theoretical model is concerned; but he believes that it is not in any sense inconsistent with Newtonian mechanics, and that it is fully justified by facts when this theory comes to be applied to actual spectra. It is, however, reasonable to suppose that although the resonance frequency (natural to the molecule) must be reached in order to excite characteristic radiation, the excitation would not continue with equal efficiency when the passing radiation greatly exceeds the resonance frequency. This difficulty becomes greatly lessened, if in fact it does not disappear, when we consider what must be the conditions of excitation in a gas, even at very low pressure, owing to the many atoms which act as exciting sources. A molecule may be excited from atoms in various directions, but co-operating with any one of them to produce a spectral line only in the direction of the alignment of the atom with the molecule.

That the frequencies of the lines of the primary spectrum of hydrogen are all given by the formula $N\left(\frac{1}{n_1^2} - \frac{1}{n_2^2}\right)$ is so well known that

it may seem superfluous to many readers to point out the fact that the system which has just been outlined would suffice to explain the hydrogen spectrum if there were no more to be explained than the primary spectrum, in its broader outlines. Therefore we are encouraged to proceed farther with our theoretical models, and inquire what we should expect in case the atoms were not exactly spherical.

Let us suppose that the shape of the atom, instead of being spherical, is a figure of revolution, similar to a spheroid in possessing one diameter longer than another. Let us assume provisionally that the positive charge is at the center of figure, and that the actual shape permits an electron to be in equilibrium at the extremity of either the

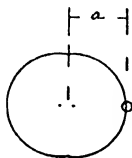


FIG. 5

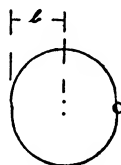


FIG. 6

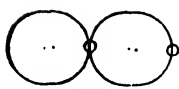


FIG. 7

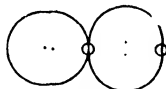


FIG. 8

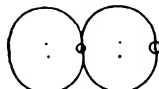


FIG. 9

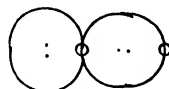


FIG. 10

longer or the shorter diameter; but that, if displaced sufficiently, without violence, the electron would take up its most stable position at the end of the short diameter, in the atom if uncombined with other atoms. The two positions of the electron are illustrated qualitatively in Figures 5 and 6. Let us designate the long radius by a and the short radius by b . Regarding a and b as constants, we can compute the frequency limits of line molecules composed of such atoms in terms of the frequency limit of atom a shown in Figure 5. We will designate the configuration shown in Figure 5 by the letter a and that shown in Figure 6 by the letter b . The combinations shown in Figures 7, 8, 9 and 10 may then be designated by $a|a$, $a|b$, $b|b$ and $b|a$ respectively, the vertical line between the letters meaning that the frequency limit of the electron in that place is under con-

sideration. Obviously, the number of combinations possible increases with the number of atoms in the line. For one atom it is 2, for two atoms, 4, for three atoms 8, for four atoms 16, and for n atoms 2^n . Some of these combinations have a certain symmetry, and the wave numbers of their middle electrons would constitute regular series, while others, if arranged in series, would manifest great irregularity. For convenience we will consider the schedules given in Table 4, which set forth some of the possible series that manifest mathematical regularity not overly difficult to trace.

In the series designated *A* the respective levels (series limits) are given by the formula $\nu = N \div (na)^2$ where n is the number of atoms in the line. In the series designated *B* the levels are given by $\nu = N \div (nb)^2$. In the series designated *C* the levels are given by $\nu = N \div [2b + (n - 2)a]^2$. If we make $a = 1$ this may be written in the form $\nu = N \div [A + m]^2$ where m is a whole number, and A a constant. Next after the formula representing the levels of the primary spectrum of hydrogen, already referred to, this is the simplest of series formulae for classifying spectral levels. In this form, however, the letter m does not indicate the number of atoms in the line, as does n in the formula given by the writer. The quantity designated by m indicates the number of atoms added to the line to progress beyond the level indicated by A .

In the three schedules *A*, *B* and *C* the lower limit of the series is 0 because the line molecules are symmetrical. However, it is possible to have regular series in which this is not so. In series *D* the progressions are irregular up to the one having four atoms in the line, but thereafter they are regular. The lower limit is not 0, but

$$\nu = N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(a + 2b)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} - \frac{1}{(2a + b)^2} \right]$$

Each level above the fifth is given by adding to this limit the quantity $N \div [2a + 2b + (n - 4)a]^2$ which may be written $N \div [x + na]^2$ which, if $a = 1$ is one of the simplest of series formulae. Such a series would be "displaced." We have admirable examples of displaced series in the spectrum of Neon. Theoretically, we might have series displaced either positively or negatively, with respect to a mathematical Rydberg series.

Series such as suggested in schedule *E* would not progress by equal increments of quantum numbers, like those of *A*, *B* and *C*, nor would

they be "displaced" substantially constant amounts, like schedule *D*; but nevertheless they might constitute true series, although the quantum numbers, computed in the usual manner, would not enable us to interpret the series, or to predict unknown levels. There may be numerous other natural types of series to which quantum numbers offer no clues, just as they do not give clues to many of Professor Richardson's levels in the secondary spectrum of hydrogen "analogous to parhelium," or to Professor Lyman's 0S level of helium, and many others, some of which we will deal with in later chapters which treat actual spectra.

Even if our model is allowable, for purposes of anticipatory exploration, we cannot assume it to be true that in real atoms which are not spherical the charge is a point charge concentrated at the center of figure, or that the ion is completely incompressible, or perfectly symmetrical, or that atoms have no more than two effective diameters. We can use these conceptions which ignore the details of inner structure,—these simple mathematical theories, as models only, for the approximate interpretation of spectra according to mechanical principles, and we must rely upon experimental data for information as to the structures that occur in nature. The discrepancies between the mathematical theory and formulae derived from observation may supply us with the necessary information to form a more rational theory as to the distribution of the charges and the mass within the atoms, and the details of the inner atomic structure.

The relatively simple models thus far considered will be found applicable to the spectra of hydrogen,—both primary and secondary, considered in some detail in a later chapter. It is too simple to suffice for the spectra of the other elements, but it may be amplified to meet them without the necessity of further amplification in this preliminary presentation of the principles to be followed in the discussions which are to come.

It will be a part of our problem, in seeking to interpret the spectra of various elements, to ascertain shapes as well as sizes of the atoms, or of the parts of atoms, which contribute to the spectra attributed to the atoms at the present time. It is obvious that these bodies may be quite complicated in contour, and may have not merely two, but a number of "effective" diameters, any of which may be in axis in the line molecule which produces a level. Moreover, we have no warrant for considering, *a priori*, that atoms, or their parts, are even

approximately of the same size. Instead of theorizing on the basis of assumed abstract principles about these matters we will await the suggestions that will be aroused in our minds by contemplating the evidence revealed by the spectra actually emitted by exciting the chemical elements under laboratory conditions.

Among the phenomena revealed by spectroscopic studies are peculiar modifications of spectra produced by exciting them in magnetic and electrostatic fields. Before considering any spectra in detail let us inquire as to what we should expect of our ideal model when subjected to such fields during excitation. Let us suppose that one of the line molecules suggested in this chapter were placed in a strong electric field. The electrons would be attracted in one direction and the positive ions in the opposite direction. These attractions must cause some distortion in the figure of the line molecule, and the nature of the distortion would depend upon the direction of the axis of the molecule in the field, as well as upon the strength of the field. Such distortions would affect the levels, and consequently the spectral lines, which are level differences. Since the line molecules would have to some extent a helter-skelter orientation (modified by a tendency to become oriented in the field), there would be a tendency toward broadening of the lines, and also, as in the case of band spectra, a tendency toward multiplication of the lines by increments, to each side of the position of the original line, the increment unit being the difference between the normal line and the mean displacement on account of the effect of field intensity upon molecules not oriented with the field. In real spectra this is called the Stark effect. We can only note here that some such effect is to be expected by our theory, leaving its magnitude without investigation. In a similar manner if a magnetic field be present, molecules moving helter-skelter in it will have distortions due to the electromagnetic forces exercised upon ions and electrons, in opposite directions, and somewhat similar broadenings and multiplications are to be expected, which in actual spectra are known as the Zeeman effect.

In considering the expected origin of a spectral line, according to ordinary mechanics, assisted by our simple mechanical model, we assumed that when an atom or molecule having a given frequency limit is communicating energy to a molecule with a lower frequency limit, which receiving molecule also is radiating the absorbed energy, the two finally cease to radiate at the same time, because of the ex-

haustion of the energy of the primary radiator. The difference between the final frequencies was taken as the frequency of the line. A little more careful consideration, however, suffices to convince anyone that not only the line would not be absolutely monochromatic, but that, since its maximum intensity would be emitted before the energy supply was too greatly weakened, it would occur at a time when the upper frequency was less than the true frequency limit. Therefore we should not expect the apparent limits, as determined from spectral lines to be, ordinarily, quite as high as the true limits; nor should we expect the limits determined from any given line, by the aid of any theoretical formula, to coincide exactly with limits determined for other lines by similar formulae. Discrepancies are to be expected, although their magnitude may in many cases be very small. We shall find such discrepancies in our examination of levels determined in the usual manners; and as we shall require a name for

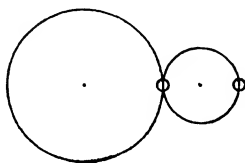


FIG. 11

this kind of a discrepancy, we shall in what is to follow call it "creep." Did we not find something of this kind we would have reason to suspect the validity of our hypothesis. Our theory does not call for the same absolute fixity of an effective level as is required by the quantum theory, where the conception is altogether different.

Let us now briefly inquire what kinds of effects we should expect if the atoms in line molecules differed from one another in size, as well as in shape, and for the sake of simplicity we will return to our simplest model, the spherical shape. If such an atom has unit radius, the force it will exert upon its electron will be $e^2 \div 1 = e^2$. An atom with a radius half as long would exert upon its electron a force four times as great, and one with a radius of one third a force nine times as great. If we had one atom of radius 1 and in contact with it an atom with a radius of $\frac{1}{2}$, forming a line molecule, illustrated in Figure 11, the terminal electron being, of course, in contact with the smaller ion, it is obvious that if the molecule were broken apart by a

pull, or by a shock which did not directly impinge upon the electrons, both electrons would accompany the smaller ion, leaving the larger atom without an electron, or ionized. But the same result might not result of necessity if the combination were broken by the absorption of radiation by the middle electron. It might then go with the larger ion. Exactly the same effects are not always to be expected when combinations break up. They may depend upon the manner in which the breaking is brought about.

A spherical ion with unit charge at its center could hold not merely two, but three or even four electrons in contact with its surface if they were brought there without shock, and undisturbed by outside influences; but the force with which they would be held depends upon the number of them, and more than four could not remain, for the repulsion of the electrons for one another would in such a case exceed the attraction by the ion. For 1, 2, 3 and 4 electrons respectively, the holding forces would be in the ratios 1, .75, .422, and .086. The smaller the radius, the greater the actual forces. It will be obvious from such considerations as these that, should some atoms be very much smaller than others, their hold upon the electrons in any molecule would be greater than the hold of the larger atoms, and we should expect subdivision under many circumstances to be accompanied by the production of both positive and negative ions. This is well recognized as the fact by chemists, in dealing with many reactions, but it has not hitherto been ascribed to the sizes of the particles directly concerned. If sizes differ, however, this is one result that we should expect, and consequently that we should look for.

CHAPTER VI

OUTLINE OF THE SYSTEM OF ATOMIC STRUCTURE

In the preceding chapter there has been presented in brief outline a conception of the grosser aspects of the structure of particles which may be applied to the study of spectra without departing from the principles of Methanics as enunciated by Newton, or the principles of the Electromagnetic Theory. In chapters to follow these conceptions have actually been applied to the interpretation of the various spectra ascribed to the lighter elements. The atoms are revealed not as bodies with great positive charges concentrated in one nuclear structure, with swarms of electrons circulating thereabout, as assumed in the theories now most popular, which originated with the speculations of Bohr, but as composite bodies made up of aggregations of ions, each with a positive charge $+e$, accompanied by an electron with its negative charge $-e$. These smaller ions, each with its electron, I have designated sub-atoms. The chemical atoms, when subjected to suitable excitation, lose some of their sub-atoms by subdivision, successive losses of sub-atoms, not merely of electrons, being characteristic of various stages hitherto ascribed exclusively to ionization.

The spectra resulting from excitation are consequences of recombinations of the parts of atoms after such subdivision. The spectral lines originate not as quanta from within single atoms or ions, but through the coöperative action of various aggregations of sub-atoms. When the excitation is complete enough to separate all of the larger and lighter sub-atoms from a group of atoms of the same chemical element, leaving only the smallest and heaviest of the sub-atoms, all of one kind, in close proximity to one another, these combine and give rise to X-ray spectra hitherto attributed to the chemical atoms themselves. The theories up to the present time have failed to consider that the atoms themselves may be broken and recombine when producing characteristic spectra. They have assumed nuclei of large charges, in spite of the fact that there are not any known means by which such charges could be held together within a nucleus, if the charges are made up of discrete units of charge $+e$, as supposed.

The writer has been able to apply the new conception successfully, and in considerable detail, to the various series spectra of the lighter elements, ascribed to various stages of ionization, in which the number of sub-elements in the normal atomic structure is found to be small; but he believes that eventually the system will be found adequate to include all spectra hitherto ascribed to any atoms in their various stages of ionization, and to other phenomena as yet unexplained by the present theories. It will facilitate our discussion of the spectra of the lighter elements to outline beforehand, in the briefest manner, the system of sub-elements of which the chemical elements are compounded.

The sub-elements, not the elements as wholes, are responsible for the atomic numbers, based upon X-ray spectra. There is a general relationship between atomic number, sub-atomic weight and sub-atomic length, which, taking the attributes of sub-element 1, which is identical with the hydrogen atom, as units, are expressed, approximately, in the following preliminary schedule, in which the possibility of isotopes among the sub-elements has been disregarded, arbitrarily.

Masses and Lengths of Sub-atoms

| | Atomic Number | | | | | | | | | |
|-------------|---------------|-----|-----|-----|-----|-----|-----|-----|-----|------|
| | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Mass..... | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 |
| Length..... | 1 | 1/2 | 1/3 | 1/4 | 1/5 | 1/6 | 1/7 | 1/8 | 1/9 | 1/10 |

The shapes of the sub-elements increase in complexity with increasing atomic number and diminishing length. These changes are probably attributable to increasing complexity of inner structure, which this discussion does not attempt to explain, although the writer believes that the shapes as well as the sizes of the sub-atoms are explicable upon mechanical principles, beyond the scope of the present work. Sub-element 1 has the simplest shape, somewhat resembling a spheroid in possessing a major and a minor diameter, as represented in Figures 5 to 10. Sub-element 2 is more complex, while sub-element 3 may be likened as to shape to a melon or a pineapple, without implying any postulates as to the structure of the surface or of the interior. Certain diameters of the lighter elements have been ascertained in terms of the length of the hydrogen atom (sub-element 1) and are given in later chapters.

Chemical elements are compounded of these sub-elements, and it has been possible to determine the structures of the chemical elements in terms of their sub-elements, but not as yet to indicate the exact arrangement of the parts in the normal atomic structures. The following schedule indicates the atomic constituents in the first ten elements, the prevailing forms only being considered, isotopic forms being ignored. This schedule has been determined from considerations of spectra, combined with considerations of atomic weight and atomic volume, and is subject to correction and revision, to account for isotopes, and spectroscopic data not yet available.

Composition of the Elements

| Number | Element | Atomic Weight | Sub-elements |
|--------|---------|---------------|--------------------|
| 1 | H | 1.008 | 1 |
| 2 | He | 4 | 1 + 2 + 1 |
| 3 | Li | 6.94 | 2 + 3 + 2 |
| 4 | Be | 9.02 | 3 + 4 + 2 |
| 5 | B | 10.82 | 3 + 5 + 3 |
| 6 | C | 12 | 3 + 6 + 3 |
| 7 | N | 14.008 | 3 + 7 + 3 + 1 |
| 8 | O | 16 | 3 + 8 + 3 + 2 |
| 9 | F | 19 | 3 + 9 + ? + ? + ? |
| 10 | Ne | 20.2 | 3 + 10 + 3 + ? + 1 |

As indicated in the schedule, hydrogen is the only element containing but one kind of sub-element. Helium, which comes next in atomic number, contains two hydrogen atoms and one atom of sub-element 2, which is about twice as heavy and of half the length of the hydrogen atom. As we have seen in a chart given on page 25, the atomic volume of helium is a little greater than that of two hydrogen atoms. The schedule indicates that hydrogen, or sub-atom No. 1 is present in helium, nitrogen and neon, all of which have relatively large atomic volume. Sub-element No. 2 is present in helium, beryllium, lithium and oxygen, while sub-element No. 3 occurs in all the elements in our schedule except the first two.

It is possible to extend this schedule to include all of the known chemical elements, but at the present time, neither the spectroscopic data nor other data are adequate to determine all the sub-elements in the normal structures, though they suffice to make it certain that

in the prevailing form of each chemical element there is present in each atom a sub-element of the atomic number of the atom, and in all those elements which, in pure chemical form develop regular arc spectra, sub-element 1 is also present. These elements are those which have the largest atomic volumes in the series to which they belong.

CHAPTER VII

HYDROGEN

Hydrogen is the lightest of the chemical elements. It occurs abundantly in the Earth, chiefly in water; but only to a very small extent uncombined with other elements. In combination with carbon, nitrogen and oxygen it provides the chemical compounds which are the chief constituents of living bodies, both animal and vegetable. Hydrogen is equally important to the chemist on account of the part it plays in inorganic chemistry, as it combines readily, under suitable conditions, with many of the other elements, in such simple proportions that in many cases the chemical "valence" may be defined as the number of hydrogen atoms with which an atom of a given element may combine directly.

When separated from its chemical compounds hydrogen occurs as a gas having two atoms to the molecule. It liquifies at -252.8°C . and solidifies at -259°C . It is appreciably dissociated into atoms at furnace temperatures. The atomic weight of hydrogen, as determined from chemical combinations, on the scale $\text{O} = 16$, is 1.008. The atomic weights of all of the other chemical elements are greater, being multiplies of a weight a little less than this, when isotopes are taken into account.

According to the schedule which we have proposed in the preceding chapter, hydrogen is not only the first element in the scale of atomic weights, of atomic numbers, and in the periodic table, but it is also the only sub-element which acts as a chemical element in ordinary chemical reactions, as well as a sub-element in the atoms of other chemical elements. As a constituent of other elements, it is of great importance. Hydrogen lines are very commonly found in or associated with the spectral lines ascribed to other elements, such hydrogen lines often being ascribed to the presence of hydrogen as an "impurity," although in many cases they are actually derived from the hydrogen, or sub-element No. 1 which forms a part of the normal structure of the other element or elements in the excitation tube.

This chapter is based upon the studies of the "secondary" spectrum of hydrogen which occupied the time of the writer for several years

from 1923 to 1931. Since those studies, important work has been done from which the conclusion has been drawn that hydrogen derived from water, is isotopic, some of its atoms having mass 2, while most of them have mass 1. However, up to the present time no comprehensive studies dealing with the secondary spectrum of the supposed isotopic form of hydrogen have been published, although accurate measurements have been made of displaced Lyman lines. The writer therefore offers his own work without consideration of the supposed isotopic form of the atom, of mass 2, for even if such a form is fully proven when all of the data have become available and have been fully studied, the heavier atoms are not supposed to constitute more than one in five thousand in the normal gas, and spectral lines due to so small a portion would, in all probability, be so weak in comparison with the lines due to the prevalent form as to be almost unobservable in the spectrum as ordinarily recorded photographically.

HYDROGEN SPECTRA

Ordinary hydrogen gas, as nearly chemically pure as obtainable, when contained in a "vacuum tube," at low pressure, and excited by the passing of an electric current of sufficient voltage and density, undergoes changes of molecular form, which occur progressively, as manifested by the spectra emitted. By using low voltages and regulating the current density, the gas pressure and the temperature, these changes may be studied by observing the spectra of the light emitted. If all of the spectral lines that can be emitted under any and all conditions whatever be included, the number of observed lines in the visible and the near ultraviolet regions alone exceeds three thousand. However, by continuing the excitation long enough and reducing the pressure low enough, especially if the temperature be very high, most of the weaker lines disappear, and others weaken so much as to leave little or no record on a photographic plate even after long exposure. The remaining lines are termed the "primary" spectrum. Their wave numbers are given approximately, but not with absolute precision by the formula $\nu = 109678 \left(\frac{1}{n_1^2} - \frac{1}{n_2^2} \right)$ where n_1 and n_2 are integers. If we put $n_1 = 1$ and $n_2 = 2, 3, 4$, etc., we have the Lyman series of lines in the Schumann region; if $n_1 = 2$ we have the Balmer series in the visible region and the near ultraviolet; if $n_1 = 3$ we have the Paschen series in the infra red; if $n_1 = 4$, the

Brackett series, and so on. The Balmer series is the easiest to observe, because most of it lies in the visible region and all of it can be photographed through glass. It has been used more than the other series to calculate the series limit, $N = 109678$. Table 5 gives the lines and levels of the primary spectrum calculated upon the assumption that the number $N = 109678$ is a constant, and that the Rydberg formula is precise. These assumptions are not absolutely true, but the errors involved in them are quite small. This table is useful for many purposes. The lines are given in the various columns, and the levels, or "series limits" are given at the foot of each column.

The primary spectrum of hydrogen, which may well be called the regular spectrum, has the unique distinction of being the most accurately represented by a simple mathematical formula of all line spectra. That hydrogen is present in many stars and nebulae is evidenced by the Balmer series of lines in the spectra of visible light from these distant bodies or systems, either as bright emission lines or as dark absorption lines. We cannot avoid the conclusion that hydrogen is very plentiful in the universe, especially in the outer portions of stars and nebulae of various types.

The wave numbers 109678, 27419.50, 12186.44, etc., are inversely proportional to wave lengths in vacuo. They are used to define exactly the "energy levels" of the quantum theory, although that theory does not regard them as true frequencies, their differences only, giving true frequencies, represented by spectral lines. We shall regard them as true frequency limits, as described in an earlier chapter. Let us repeat here that the wave numbers of all spectral lines are to be regarded as either simple or compound differences between frequency limits, or, as they are called by the quantum theory, "levels." For our purposes we ignore completely all ideas or assumptions that there is any natural dependency between the frequency of radiation and the energy of the units possessing the frequency. As a matter of mathematics alone, it is a fact that the lines have frequencies which are differences between levels, when the levels are expressed in wave numbers, which is the usual and the most accurate way of expressing them. We are depriving ourselves of no mathematical advantage, or convenience, when we regard the levels as frequency limits and not as energy levels.

When excited by passing a current through pure hydrogen gas, the primary spectrum always is accompanied by a continuous spec-

trum which has its upper limit at $N = 109678$, in the Schumann region, and extends toward the visible region. This continuous spectrum, or another overlapping it, may extend entirely across the visible field and well down in the infra red. It represents quantities of energy that are large in comparison with the energy contained in the spectral lines. When the secondary spectrum is present as well as the primary, the continuous spectrum extends beyond the limit $N = 109678$ to the limit 117743. The secondary spectrum never appears without the primary. The absorption spectrum of hydrogen in the ultraviolet region manifests a peculiarity which is very important to our interpretation of it. If the source of radiation absorbed is pure hydrogen gas, both the emission spectrum and the absorption spectrum terminate abruptly at 117743, but if helium be used as a source of the light which gives the continuous background for absorption in hydrogen, the absorption spectrum of hydrogen extends beyond this limit, in a series of absorption bands.

Ordinary hydrogen gas cannot produce the primary spectrum, or any line spectrum, until it has undergone some change caused by heat, the absorption of radiation, or the passage of current through it. If, to a discharge tube containing hydrogen gas at low pressure a difference of potential be applied, electrons being released to traverse the gas by the use of a hot wire electrode, current will pass at all voltages impressed in the right direction, but no spectral lines will appear until the voltage has exceeded a certain critical value. However, the gas will be excited, and emit a continuous spectrum, the upper limit of which is proportional in frequency to the impressed voltage. The interpretation which the writer places upon this fact, which is well established as a fact, is that the continuous spectrum emitted under these conditions comes from the molecules of the gas, the excitation being insufficient to separate any of them into atoms.

When the impressed voltage reaches a certain critical value, which depends to some extent upon temperature and pressure, but is in the neighborhood of 15.8 volts, both the primary spectrum and the many-lined or secondary spectrum appear together. If, as assumed, the gas pressure is very low, the secondary spectrum then fades out, leaving the primary spectrum alone, with its accompanying continuous spectrum, which may be confined to the ultraviolet region, or may be sufficiently intense to extend over the entire visible field and give it a faintly luminous background. Thereafter, it is pos-

sible to maintain the primary spectrum at a reduced voltage. None of the primary lines will disappear altogether if the voltage is not reduced below 13.5 volts, though some of them may be greatly weakened, but when the voltage is reduced below 13.5 the fainter lines disappear one by one in each series, until at 10.2 volts only one line,—the first Lyman line in the Schumann region, the wave number of which is 109678 ($1 - 1/2^2$) remains. If the voltage does not fall too low the other primary lines may be restored by raising it; but if the current is interrupted, the lines cannot be restored by raising the voltage to a less value than 15.8, which reestablishes both primary and secondary spectrum together.

Hitherto it has been argued that the primary spectrum is emitted by separate atoms and the secondary spectrum by molecules, the voltage 15.8 being that necessary to dissociate the molecules into atoms (though not necessarily representing the energy of dissociation). This explanation, however, is not adequate, for the voltage 15.8 is as necessary to initiate the secondary spectrum as the primary, and thus would indicate, by the same argument, that atoms are necessary for the secondary spectrum. We accept the first part of the usual hypothesis, that atoms are produced by dissociation at this potential, and that single atoms must be present before the primary spectrum may be excited; but not the second part,—that these atoms, singly, are responsible for all of the lines of the primary spectrum. On the contrary, we hold that the lines of both primary and secondary spectrum require for their formation both free atoms and molecules, and that the differences between these spectra arise because of differences in the arrangements of the atoms in the molecules which produce the various levels.

All of the lines of both the primary and the secondary spectrum are explicable on the hypothesis that the hydrogen atom possesses two different diameters, at opposite ends of either of which electrons may be attached in stable equilibrium, when the gas pressure is low enough to permit the formation of line molecules upon suitable excitation. We may represent such atoms graphically as in Figures 5 to 10. The primary spectrum is emitted by the coöperation of molecules in which all atoms have their a diameters in line, while the various systems known collectively as the secondary spectrum require some line molecules, often many, with atoms with b diameters in line. The primary spectrum persists at low pressures and high temperatures

when the secondary spectrum fades out because under those conditions there are lacking influences to bring about the *b* alignments, once they have been changed to *a* alignments by excitation.

If this hypothesis be tenable, it was a mistake to attempt to outline a structure of the hydrogen atom to account for the primary spectrum only. That spectrum gives evidence only as to one dimension of the atom, while the secondary spectrum supplies data regarding another. But the classification of the lines of the secondary spectrum alone, without their interpretation, at first appeared to a task so difficult as to be almost if not quite impossible. Their measurement and classification required years of devoted effort by numerous investigators, and liberal expenditures for equipment. It has not yet been fully accomplished. The present writer's contribution to this work has been confined to classification, and to interpretation of the work of others, and while he has devoted to it some years of study, his part in the classification appears to him almost negligibly small in comparison with the work of others. To discuss adequately the classification of the secondary spectrum of hydrogen would require considerably more space than is contained in this book, including several score of tables and charts. Finally, after Richardson had outlined two extensive systems in the visible region and Dieke and Hopfield two systems in the Schumann region, using all of the work of others, but an entirely different scheme of interpretation, and adding some classifications of his own, the present writer finally succeeded in developing a rational scheme which accounts for all of the principal systems of lines known, including all of the lines of considerable intensity. Table 6 gives the levels, in wave numbers, of the principal line molecules of hydrogen composed of four atoms to the molecule, or less, with a few molecules of greater length. These are the principal levels that contribute to the secondary spectrum of hydrogen. The available data are much more extensive than this table, including many level differences between molecules having five, six or more molecules in line. This table includes much new data hitherto unpublished. Space cannot be taken here to discuss the band structures. We will confine ourselves to interpreting the levels set forth in Table 6.

The left hand column in Table 6 indicates the molecule responsible for the level, or frequency limit. The level, in wave numbers, is given in the second column, and important wave number differences

between somewhat similar molecules in the third column, these differences also being differences between nulls in several important systems of bands. In the space following the third column are given differences which produce the principal nulls of the more important band systems, and other important differences which enter into the compounding of the more complex nulls from the simpler ones. The levels and the differences all are derived from analysis of the lines and bands of the hydrogen spectrum, and do not depend upon the interpretation as to source placed upon them in the first column of the table. The level differences given in the columns designated by the letters *a*, *b*, *c*, etc., are found in the following band systems:

- a. Levels of the "Primary" Spectrum.
- b. Principal Levels of Richardson's "Ortho" Bands.
- c, d and e. Principal Levels of New Bands by Venable.
- f. Principal Levels of the 00 null of Richardson's Infra-red "Ortho" Band System, found by Venable.
- g. Principal Levels of New Band System (Venable).
- h, i, and j. Principal Levels of Richardson's "Para" Systems.
- k, and l. Principal Levels of Dieke & Hopfield's Ultraviolet Band Systems, found in absorption, with hydrogen used as a light source.
- m. Level increments found by Venable, for Hopfield's absorption bands with helium used as a light source.

The consistency of the table will be illustrated by considering the value of *b* (taking *a* = 1) derived from the quantum numbers of the several regular series, assembled for convenient comparison in Table 7. The quantum numbers, designated by *q* in Table 7, are derived from the wave numbers of the levels by the formula $q = (109678 \div \nu)^{\frac{1}{2}}$. The part of the table marked A gives the levels of the primary spectrum, in which the quantum numbers progress by increments of 1. These numbers thus represent each a single length,—from the electron whose frequency limit is under consideration, to the terminal electron or ionic center. The part of the table marked B gives quantum numbers, each of which represents a single distance, but not multiples of a single unit of length. These quantum numbers, however, progress with increments of approximately unity. If we assume that the increments are actually unity, we find the distance *b* apparently slightly variable. The mean values of *b* are given in the last column. The series designated C do not combine with one

another to produce lines or nulls, but they combine with some of the other levels, given in Table 6. They are picked out for the purpose of numerical comparison. These quantum numbers also represent approximately single lengths, but the distance b apparently is slightly, though regularly variable.

We will not here enter upon a discussion of reasons why the b dimension appears to be more variable than the a dimension, or as to whether this is a real variation in length, or some more involved matter, due to the structure of the atom, or to actual deformation under pressure, for we have not yet arrived at a point where such discussion may be followed up with profit.

In the three groups of progressions in Table 7 the effective quantum number represents, at least approximately, a single length. In cases where the molecules are unsymmetrical this is never so, and the quantum numbers do not assist directly in ascertaining the molecular configuration. Such configurations are $b|a$, $bb|a$, $ab|ab$ and the like. $b|a = 35233.79$, for instance, is a most important level, being the fundamental level of Richardson's "Para" band systems. Its quantum number is 1.76 (approximate). For our purposes this is useless. As the molecule is not symmetrical we must consider the force of each electron and each ion as acting upon the middle electron separately, and add them up to obtain the actual force. This gives us for the frequency $\nu = N/b^2 - N + N/4 = 35233.79$, whence we get $N/b^2 = 117492.29$, which is somewhat less than the value of $b|$ in Table 6; but the configuration is different, and the discrepancy is not more than we might expect from the variations in the values of b found in Table 7.

Similar calculations for any of the molecules in Table 6 will give reasonable values for b . This method of accounting for levels that do not fall within the expectations of ordinary series is new, and of great value, both in accounting for levels already known, but in predicting (approximately) unknown levels to be sought for.

The process of excitation of ordinary hydrogen gas is thought of as comprising a series of steps, somewhat as follows: Initially the gas molecules, comprising two atoms each, are not in the form of line molecules, with one electron at the end of the line, but a form in which the electrons are both somewhat between the ions,—a form which we may call a ring molecule. Electrons impinging upon them, and partially penetrating them, excite continuous, non-characteris-

tic spectra, the highest frequency of which depends upon the voltage. If this frequency be high enough, the electrons in the molecule absorb some energy, and the shape of the molecule is modified, assuming one of the several possible line molecule forms containing two atoms. These line molecules, in turn, are modified by excitation, one form being ionized or dissociated at about 15.8 volts. The dissociated atoms are both *a* and *b* varieties, and they combine with the line molecules already present, as well as with one another, to produce longer molecules, of the various forms indicated in Table 6, which coöperate with one another in the production of both the primary and the secondary spectrum. With continued excitation at low pressure, the *b* variety of atoms are converted to the *a* variety, by shifting of the electrons, and finally no atoms of *b* orientation are left in the gas, whereupon the secondary spectrum is not in evidence.

CHAPTER VIII

HELIUM

Helium is the second "element" in the scale of atomic numbers. Commonly it is classed with hydrogen, as forming a short chemical series. It occurs in the atmosphere, as a rare gas, of molecular weight 4, not breaking up into smaller units readily, or combining with other chemical elements under temperature conditions with which the chemist ordinarily deals. Helium occurs associated with combustible natural gases in certain natural gas fields, and its chief source of supply is such natural gas. It also occurs occluded in certain minerals, from which it is liberated by heating. It also is produced in the emanation of radium and other radioactive elements. Seemingly, helium is a constituent of other elements,—probably of many of them; or else some constituent of helium also is a constituent of other elements, and combines to form helium when it is liberated. The atomic weight of helium is determined without chemical methods, and therefore cannot be said to be known with great accuracy; nor does it inform us whether to expect the atoms to have a single form, or to be isotopic. The atomic weight is given as 4.

The atomic volume of helium is somewhat over twice that of hydrogen, or a little greater than that of the hydrogen molecule. This circumstance, of itself, suggests the idea that helium may consist of two atoms of hydrogen and something else, the new part having mass 2. This, however, has not hitherto been thought to be the case, the general opinion being that the helium nucleus, of mass 4, is indivisible, and that it has a charge of $+2e$, being capable of losing two electrons, and producing an ion of mass 4 and charge $+2e$. Upon assumption that this is true, Bohr extended his quantum theory of atomic structure adapted to interpret the hydrogen spectrum to include helium, incorporating such additional postulates as were necessary to go with this interpretation. We do not accompany Bohr in any of these assumptions, but on the contrary follow the suggestion made us by the atomic volume, the atomic weight, and the fact that the atom is chemically neutral, and consider helium as composed of two sub-atoms of mass 1 and one sub-atom of mass 2. The

helium spectrum is then found to be of the character we should expect from such constituents combining in certain well defined ways, and we are enabled by carefully considering it, to ascertain the dimensions of the smaller and heavier particle.

Before we examine the spectroscopic evidence, we must divest ourselves of the prejudice favoring the opinion that the helium atom is indivisible, and capable of being doubly ionized. This is not drawn from examination of the excitation of helium, or of its spectra, but from the fact that helium is a product of radioactive elements, or at least seemingly so. It is possible to produce, from helium, ions that are deflected by electric and magnetic fields in precisely the same way as are the positive rays emitted by radium and other radioactive elements. The atomic weight of helium being 4, it was assumed that these ions had mass 4, and consequently they must have charge 2, for a positive particle of mass 4 and charge 2, would, according to theory, behave as a projectile in exactly the same way as a particle of mass 2 and charge 1. Two alternatives were open,—the first to consider the helium atom, ionized, as expelled in its entirety from the radioactive element, in which case it must be doubly ionized and must be so constructed as to be capable of holding together in the doubly ionized condition. This is the alternative taken by Bohr. The other alternative is that the helium atom contains a unit of mass 2, capable of losing one electron only; and that this is the particle emitted by radium. In that case, these positive ions, known as alpha particles, must acquire other particles after expulsion before they produce ordinary helium. The other particles are, as we shall see, hydrogen atoms. Since it is impossible, by the methods of positive ray analysis as now developed, to distinguish between a particle of mass 2 and charge 1 and a particle of mass 4 and charge 2, if there be either, we must look elsewhere than to this kind of evidence to settle the matter.

THE SPECTRA OF HELIUM

Helium is the first element that was discovered by purely spectroscopic methods. Certain helium lines were found in the Sun before the element was known to occur on Earth. Later, other lines, found in stars, were first attributed to hydrogen, but later found producible in helium under terrestrial conditions, but not in hydrogen. It will facilitate our discussion of helium spectra to give a brief account of

the systems of lines which compose it, not in the order of their discovery, nor of their analysis, nor of the stages of their excitation from ordinary helium, but in the order of their increasing complexity.

The Regular Spectrum of Helium, usually ascribed to the ionized atom, of mass 4 and charge $+e$, resembles the regular spectrum of hydrogen in the mathematical arrangement of wave numbers, except that the frequencies are a little greater than four times those of the hydrogen lines, and the progressions are not quite as regular as in hydrogen. For convenience in comparison with other levels, these levels and the corresponding hydrogen levels are set down in the middle columns of Table 8. The levels are from Fowler, page 95. They were calculated by the formula $\nu = 4 \times 109723.22 (1/n_1^2 - 1/n_2^2)$ where n_1 and n_2 are whole numbers. Series are known corresponding to this formula, where n_1 is 1, 2, 3 and 4.

The Normal Spectrum of Helium, usually ascribed to the neutral atom, comprises numerous series of lines. In the visible and near ultraviolet region the normal spectrum is usually regarded as comprising two entirely separate systems with no intercombinations, known respectively "parhelium," or the doublet system, and "orthohelium," or the singlet system. To each of these systems are usually ascribed four entirely distinct series of levels, which are given for comparison in Table 8. We note here that the levels designated δ , P, φ and F are suspiciously like one another, and approximate the levels of the regular series. In our preliminary theoretical chapter we discussed the possibility of a phenomenon which we termed "creep." Bearing this in mind, we cannot dismiss, arbitrarily, the possibility that these levels which are so nearly alike may be due to the same physical cause,—most probably, in the normal spectrum, the presence of hydrogen atoms in the a configuration, in which case these two systems are not as independent as they have been supposed to be. They occur together, under the same conditions of excitation.

The Secondary Spectrum of Helium, in the visible region and the near ultraviolet region, resembles the secondary spectrum of hydrogen in many important respects, but is more complicated in others. Such spectra usually are ascribed to "molecules," and not to atoms; but this seems not to harmonize with the idea that the ordinary condition of helium is atomic, not molecular. In such spectra the lines are very numerous, and comprise many subordinate series, with lines separable by more or less regularly spaced intervals, and diminishing

in intensity from a point called a head or a null, where a line might be expected, but usually is not found at all, or is very diffuse. Often several subordinate series have a null in common. Curtis was the first to measure such bands in helium. In January, 1915, Professor Fowler pointed out that certain of the heads of bands photographed by Curtis, who had been called into military service, were related to one another in a manner similar to the relationship of lines in series spectra attributed to atoms, giving the formula

$$\nu = 34295.86 - \frac{109679.22}{(m + .928427)^2}$$

as approximately representing the leading lines of one component of a doublet system, and

$$\nu = 31956.22 - \frac{109679.22}{(m + .964402)^2}$$

as approximately representing the leading lines of another doublet system. Curtis, after his return, resumed his work, and published a series of papers on this spectrum, determining the nulls as accurately as possible, and from them the levels between which the nulls are differences, as is done for series spectra ascribed to atoms. These levels, as found by Curtis, are given in the first two columns of Table 9, followed by their quantum numbers, and other data referred to later. These levels represent only the principal series. There are many other levels which contribute to the band structure, and are necessary to take into account if all of the lines are to be explained, but which, for our present purpose, need not be known. There may be slight inaccuracies in the levels given in Table 9, owing to the method of determining the nulls, but these are so small that they cannot much vitiate the conclusions at which we shall arrive by using them.

An *Orthohelium Spectrum in the Ultraviolet* was discovered by Professor Lyman.¹ In this series the lines differed from one another by the same wave numbers as the *mP* levels of orthohelium in the visible region, but the upper level came at a frequency not explained by any theory or anticipated by any series formula. Lyman found the 0S level at $\nu = 198298$, which since has been determined with

¹ *Astrophys. Journ.*, July, 1924.

more accuracy by Paschen as 198307. Professor Lyman found other lines which will receive further discussion, but were not satisfactorily accounted for by the theories then extant.

A Parhelium Spectrum in the Ultraviolet. In April, 1930, Professor Hopfield reported a new series of bands in helium, giving the heads of the bands, approximately, as set forth in the first column of Table 10, from which I have computed that these heads are due to a new level at $\nu = 151229$, in combination with the π levels of parhelium given in Table 8. Hopfield also extended the known lines of the regular series.

Precision measurements of the Lyman lines, including some of doubtful origin, were made by Kruger, in 1930. He gives, with other data, the following:

| | |
|-------------------------------|--------------------------------------|
| $\lambda = 600.019 \text{ A}$ | $\nu = 166663$ as a strong band line |
| $\lambda = 601.418 \text{ A}$ | $\nu = 166274$ as $0S - 1S$ |
| $\lambda = 357.507 \text{ A}$ | $\nu = 279714$ |
| $\lambda = 320.392 \text{ A}$ | $\nu = 312117$ |

Line 357.507 appears only when 601.418 is present. The levels responsible for three of these lines have hitherto not been traced. There are other lines shown on some of Professor Lyman's plates, measurements or classifications of which have not been published.

Just as the molecule of hydrogen must be modified or broken into parts before either the primary or the secondary spectrum of hydrogen may be excited, so the normal helium molecule must be modified and line molecules formed before any line spectra can be emitted by helium. The first lines that present themselves as the excitation is increased, if the pressure is not exceedingly low and the temperature high, belong to the many lined, or secondary spectrum. Upon continuous excitation, especially at low pressure, this gives place to the normal spectrum, which at very high temperatures and more intense excitation gives place to the regular spectrum, which appears without the normal spectrum in certain "helium stars."

There has been much work on all of the helium spectra, and the levels recorded in our tables are known with considerable precision, as well as their classifications. With the exception of the classification of a few lines in the ultraviolet region, our present investigation will be confined to interpretation of the levels calculated by others, accepting their classifications. Our presentation will be simplified

if we anticipate the results by a short statement of a preliminary nature, which the reader will not regard as intended to be complete, but only as leading the way to a more critical presentation of what actually has been found.

Let us assume that the helium atom is composed of two atoms of hydrogen (sub-element 1) and one atom of sub-element 2. We will first show that all three electrons may be in contact with the smaller ion when the helium atom is in its normal, or unexcited state. For this purpose we will assume that both ions might be spherical, the smaller of half the diameter of the larger. We have already seen, in a former chapter, that the force with which each of three electrons would be held to a spherical ion is $.422 e^2/R^2$. If R is the diameter of the larger ion, $R/2$ is the diameter of the smaller, and the force which would hold the electrons to the smaller ion is $4 \times .422 = 1.688$ times that with which one electron would be held by the larger ion. It is obvious, therefore, that a configuration is possible, in which all three electrons would be in contact with the smaller ion, before excitation, even if the exact configuration is not known; and it also is evident that if the shape of the ions does not depart from the spherical by a considerable amount, all three electrons may be in contact with the smaller ion, even though it is not spherical. We must expect, therefore, that the helium atom in the ordinary inert gaseous state, comprises one ion of sub-element 2, with three electrons in contact with it, and two ions of sub-element 1 held to it by the preponderating attraction of the three electrons over the repulsion of the ion of sub-element 2.

The first stage in the excitation of line spectra in such a gas must be converting the atom into a line molecule by displacing one of the electrons sufficiently. If this is done by the absorption of radiation, excited by electron impact, it would take place at some voltage less than 1.68 times the ionization potential of hydrogen, which is 13.5. The critical potential for this change would therefore be less than 22.7 volts. It would merely straighten out the atom into a "line molecule," without dissociation or ionization. Not knowing the exact shapes of the particles, we cannot compute the exact configuration of the unexcited molecule or the critical potential which would cause the change. It is quite possible that this potential would not be sharply defined, and as it does not result in either ionization or the emission of spectral lines it might be difficult to detect experimentally, especially

if sought only by the ordinary methods. After this change has been wrought, the line molecules produced could be ionized, as well as dissociated, by radiation produced by the impact of electrons at higher potentials. There has been much discussion concerning the exact ionization potential of helium, earlier measurements placing it at 25.5 volts, and later corrections at 24.6 volts, which agreed better with the requirements of the quantum theory.

If all of the ultraviolet spectra of helium were fully known we would be able to begin our discussion of the helium spectra with the discussion of the levels produced by line molecules containing no more than two atoms, the levels of all of which lie in the ultraviolet. But since the ultraviolet spectra are not fully known, and a part of our problem is to discover them, we are constrained to begin our study with the spectra in the visible region, the levels of which are due to line molecules containing a greater number of atoms in line.

For the Curtis band levels the effective quantum numbers, the molecules which are responsible for the levels, and the effective radii of the ions derived therefrom, are all given with the wave numbers, in Table 9. For the normal spectrum, the leading levels only, with quantum numbers, are given in Table 11.

In determining the levels in both of these tables (all of this work having been done by others, the writer contributing nothing new to these classifications), series formulae were calculated from the lines in the usual manner, the mathematical laws of such series being quite independent of whether the investigator has in the back of his mind the postulates of the quantum theory or no physical postulates at all. Our original work begins with the analysis and interpretation of the effective quantum numbers, not with their determination. In all eight of the series of levels of the normal spectrum these quantum numbers progress regularly by increments of approximately, but not exactly 1. In the *P* levels of the two band systems they increase by almost exactly 1. The *2S*, *3S* and *4S* levels of the first band system increase in a similar manner, but the *1S* level of that band system is separated from the *2S* level by a larger increment, and there are a number of band levels for which series are not reported, whether because not present, or because the analysis was not carried far enough to discover them we will not now inquire.

In all cases where the levels increase in quantum numbers in a regular manner, by increments of approximately unity, becoming more

nearly unity as the term numbers increase, the same explanation applies,—that there is an addition of one atom of sub-element 1, in the a configuration, to the appropriate end of the line, in a molecule the middle part of which is symmetrical. We have assumed that the a diameter of sub-element 1 is practically invariable, in configurations of this kind, because we have found it so in our studies of the primary spectrum of hydrogen. Because of the regularity of the spectrum of “ionized” helium, we also have assumed that the a diameter of sub-element 2 is practically invariable. The other dimensions of sub-element 2 are not so constant. As in case of the b dimensions found for hydrogen, we must call these lengths designated b and c “effective” diameters, because we have not taken into account, in determining them, the distribution of the charge within the ions, but have assumed the equivalent of a central charge. The “effective” radii have been determined from the “effective” quantum numbers.

These sub-atomic radii, however, are not equally variable, as is seen upon examination of the tables. The b radii correspond to the b radii of hydrogen, but there are two of them, differing but slightly, while hydrogen has but one. To account for the σ and S levels, both normal and band, we are constrained to recognize a new dimension, designated by c , of which there appear to be four varieties, sufficiently different from one another to be quite distinctly defined. The necessity for considering so many independent dimensions in sub-element 2 was not anticipated by the writer, who exhausted all his resources for alternative explanations in the hope of being able to reduce the number, originally trusting that one variety of c dimension would be able, by selecting suitable combinations, to account for all of the various levels. He adopted the view that there are four possible c dimensions when he found that this not only affords the best interpretation of helium levels, from a mathematical point of view, but also that these same dimensions are found applicable in the interpretation of the spectra of other elements, particularly lithium, which is discussed in the next chapter.

In this and subsequent chapters, where line molecules are designated by letters, the letter represents, in each case, the radius of the atom in the line. The size, or rather the atomic number of the sub-atom is the subscript following the letter, while the accent mark above designates which variety of the dimension is present. Thus a_2 means that sub-element 2 is in the line at the place indicated by the

position of the letter, with its a diameter in line, while b_2' indicates that the same sub-element is present, but with its b' diameter in the line.

The shortest radius of sub-element 2 is its c diameter. It occurs in the line molecules responsible for the σ series of levels of the normal spectrum and apparently in the 1S level of Curtis second band system. It will be found again in the S level of Li III. The c' dimension is found in helium (so far as our present analysis extends) only in the 1S level of the first band system; but it is found again in certain of the singlet terms of Li II. The c'' dimension is found in helium in the 2S, 3S and 4S levels of the first band system, and in lithium in the s levels of Li II. The c''' dimension is found in the S levels of orthohelium, and in the 2S and 3S levels of Li II. These same dimensions are found to indicate the presence of this sub-element in other elements heavier than lithium.

Of these c dimensions the first one to be determined with reasonable certainty is c found from the σ levels of parhelium, where the initial line molecule must be symmetrical, on account of the regularity of the subsequent progressions, and is assumed to be composed of four atoms, similar and similarly aligned. That there is such a sub-atom was later confirmed beyond reasonable doubt by its being found alone responsible for the S level of Li III. It then seemed possible to explain the S levels of orthohelium as due to the combinations set forth as alternate in Table 11, but this was finally set aside as improbable, and also unnecessary, upon the discovery of the c''' dimension in Li III. These facts are mentioned here, chiefly to point out that the system here proposed must be judged not only by its mathematical fitness to account for the various levels of each element, considered by itself, but also by the consistency of the scheme as a whole, the scheme requiring that the same sub-elements enter into the structures of different chemical atoms, though in different arrangements.

The combination $b'b|bb'$ to which the 1π level is ascribed in Table 11 is responsible for only one of the two levels, which form a doublet. The other level is probably occasioned by the combination $bb'|b'b$, the slight difference being sufficient to produce the separation found in the several series of lines for which 1π is the upper level. This separation diminishes, as it should, as the length of the line molecule is increased by adding atoms of hydrogen. The variation in doublet separations is one source of data by which we may hope to be enlightened concerning inner structure of the sub-atoms.

There are in our tables certain levels for which the dimension a_1' has been employed. In the case of helium these are found in Table 9 in the Z , X and D levels of the first band system and the S and D levels of the second band system. In Table 11 they are found in the series of P levels of orthohelium. This is a dimension attributed to sub-element 1, but not found in the hydrogen spectrum as yet classified, though it might be found necessary to account for some of the unclassified portions thereof. However, it seems to the writer that it is more probable that this configuration of the hydrogen atom is one that may be produced when the sub-atoms are separated out of the helium atom, but not by the breaking up of the normal hydrogen molecule or line molecules formed therefrom. This seems the more probable because a similar modification of the a dimension of sub-element 2 is found in the spectra of elements heavier than helium.

The P levels of orthohelium, would appear to arise as a result of separating from the normal helium atom, after some modification, or possibly before it has been converted into a line molecule, of both the hydrogen atoms in its structure. There are, as yet, insufficient data to resolve this question completely. The writer has tried many other combinations in endeavoring to account for the P levels, but has not found any even approximately satisfactory. It would seem that the separation just suggested would leave the sub-atom 2 in the c configuration, and there is evidence that this form of the atom is responsible for a certain level in the ultraviolet region which we have not yet discussed.

In Table 11 the δ and D levels are ascribed to the same molecules, and the φ and F levels are ascribed to the same molecules, the latter being identical with molecules responsible for the primary spectrum of hydrogen. It is possible,—in fact, I still consider it probable, that the δ and D levels also are the same as the regular levels of hydrogen in origin, the initial levels of these series being due to $a_1a_1|a_1$ instead of to $a_1a_2|a_2a_1$ as in the table, though mathematically either form appears possible, the discrepancy between the levels as indicated by wave numbers in Table 8 being due to “creep.” This requires further inquiry for its justification, which we will now attempt.

It is well known that when a series formula is calculated to fit the wave numbers of three spectral lines belonging to a series it may be used to calculate other lines of the same series, approximately, without change in the constants of the series, although the lines so cal-

culated seldom or never agree exactly with the lines as actually observed. In spite of many efforts to devise formulae that apply exactly to all the lines of any series, this object has not been attained. We may take any three lines to calculate the constants of a series, but the series limit so determined will differ somewhat, depending upon which lines are selected. Discrepancies of this kind are found even in the most regular of all series, the primary spectrum of hydrogen. They are appreciable in the primary spectrum of helium, as set forth in Table 12. In the normal spectrum such discrepancies between calculated and observed lines are much greater, and the evidence is quite conclusive that, to some extent, the levels themselves vary with the combinations into which they enter, and are not absolutely fixed frequencies, or energy levels, as has hitherto been assumed in all series formulae and the calculations of lines and levels based upon them. This is immediately apparent when we compare a series of levels calculated by the use of one series of spectral lines with a series, supposed to be the same, but calculated from another series of spectral lines. The known spectrum of helium enables us to do this very conveniently.

In Table 8 the four series of levels σ , π , δ and φ assigned to parhelium and the four other series S , P , D , and F assigned to orthohelium, are given, as calculated from different series. The levels as ordinarily taken, calculated by Fowler, from the series $1\sigma - m\pi$, $1\pi - m\sigma$, $1\pi - m\delta$, $1\delta - m\varphi$, $1S - mP$, $1P - mS$, $1P - mD$ and $1D - mF$ have set alongside of them for ready comparison corresponding levels calculated from the combination series $1\sigma - m\sigma$, $1\pi - m\pi$, $1\sigma - m\delta$, $1S - mS$, $1P - mP$ and $1S - mD$, in each case assuming the initial levels of σ , π , S and P to be the same as in Fowler's series. It is noteworthy that these series of levels differ from one another not only substantially, but also systematically, so that the major part of the discrepancies cannot be due to inaccuracy in the measurement of spectral lines. Either there are separate sets of levels for the combination series, which nobody asserts, or the levels are not as fixed as past theories would have them. In fact, these discrepancies are in many cases greater than those between the δ and D levels calculated by Fowler, and this gives us further justification for ascribing these to the same origins in Table 11.

The σ , π , S and P levels, however, cannot be accounted for as of common origin. It is, however, possible that the "creep" is due in

larger measure to lowering the higher levels different amounts when entering into different combinations than on modifying the levels produced by the longer molecules, which are of lower frequencies. If we take the regular series as representing the levels of the longer molecules correctly we would have to take a different value for the upper level in each combination. The values of the 1π level computed from the principal series in this way, using only one component of the doublets, are given in Table 13, in the left hand side of the table, and those of the $1P$ level on the right hand side of the table. It is believed that the shift is, for the most part, in the upper level. However, it becomes impossible hereafter for us to expect absolute correspondence between any two determinations of any level calculated by different series. In the case of helium we clearly have a considerable multiplication of mathematical levels, which does not mean a corresponding multiplication of physical sources of levels, even though there remain difficulties in ascertaining beyond all doubt exactly what the origins may be.

The writer wishes here to remark that this phenomenon of "creep" plays an important part in determining the levels of the molecules of hydrogen revealed by the secondary spectrum. It was not discussed in the preceding chapter because there it would involve a lengthy discussion of band spectra. The maximum creep found in the secondary spectrum of hydrogen is very much less than that found in the normal spectrum of helium; and it appears that the creep found in the spectra of elements heavier than helium is, in turn, greater than that found in helium. It appears likely that in very many instances the great multiplication of levels found for the normal spectra of some of the heavier elements is due in large part to this cause. The classification of spectra, however, is not yet nearly complete enough, nor this scheme carried far enough to make it possible to determine the creep in spectra generally.

We now turn our attention to the spectrum of helium in the extreme ultraviolet or Schumann region. We have mentioned that Professor Lyman discovered a series of lines whose members are expressed by $0S - mP$, where the mP levels are substantially the same as those of orthohelium, in the visible region. Lines corresponding to $0S - 1S$ and $0s - 1\pi$ were also found, these being combination and intersystem lines. The $0S$ level as corrected by Planck was found to be 198307, which figure we shall employ, without more

critical inquiry as to its accuracy, or as to the phenomenon of creep in this spectral series. To account for this level 198307 I have tried all possible combinations of molecules using two atoms of any of the diameters found in the studies of other helium spectra. There are only two which appear mathematically possible, $c_2'' \mid a_2$ and $c_2' \mid b_2$. $c_2'' \mid a_2 = 198307$ gives us $c_2'' = 527576$ and $c_2'' = .4559$, which is in good accord with what we have found elsewhere, but on the other hand if we take $b_2 = .482$ and $c_2' \mid b_2 = 198307$ we get $b_2 = 472093$ (approximate) and $c_2' = 552376$, whence $c_2' = .4456$, which is in good accord with the value obtained from the 1S level of the first band system. It is possible that there are two levels, due to these two different molecules, both comparatively near together. Of these alternatives, however, $c_2'' \mid a_2$ seems the more probable.

Professor Hopfield discovered a band system, the heads of which are represented by the formula $0\sigma - m\pi$ where the $m\pi$ levels are the same as in parhelium, as given in Table 8. The heads of these bands as given in wave lengths by Professor Hopfield are set forth in the first column of Table 10. From these and the levels the upper level of this series is found to be approximately $\nu = 151229$. The operations of this calculation are given in the table. The effective quantum number of this level is .8516, which may be ascribed to the molecule $c \mid c$, giving $c = .4258$, which is very close to other values found for c_2 from other series. This level, predicted by the writer's scheme, is not an expected level according to previous theories of spectra. From this level we can predict an approximate value of the level due to $c_2 \mid$ as $4 \times 151229 = 604916 \pm$. We should expect the level due to the atom to be somewhat greater than this, and we shall find such a level shortly.

There are two lines in the Schumann region that occur under the same conditions of excitation. One of these is $\nu = 166274$, ascribed to $0s - 1S$, and the other is $\nu = 279714$. Because these occur together it seems very likely that they have a level in common, the same molecule coöperating to produce both lines, but with different other molecules. In this case the missing level may be $279714 + 198307 = 478021$. The quantum number of this level is .479, which is less than we have found for any values of b_2 , our lowest, derived from other spectra, all of which involved several atoms in the line, being .482. The discrepancy is larger than the writer would expect but not so great as to place the combination out of the question, as it is in the correct direction.

There is still another line for which a possible explanation may be suggested, subject to doubt and correction. It is $\nu = 312117$. This might be due to $b_2' | - c_2 | c_2$, in which case, since $c_2 | c_2$ is known, gives $b_2' = 312117 + 151229 = 463346$. The quantum number of this level is $b_2' = .4865$, which is in fair accord with expectations.

If either of the lines 279714 or 312117 are band lines, it will be due to a more complex combination than has been suggested, and the discrepancies found may be reduced, if they are true discrepancies. The data available to the writer are not sufficient to enable him to determine the nature of these lines more positively.

There is still one very strong line at $\nu = 166663$ to be accounted for, if we disregard a number of weaker lines that appeared on Professor Lyman's plates, for which measurements were not published. This line may be due to the combination $c_2 | - a_2 |$. As we know a_2 (not allowing for creep) this would give us $c_2 = 438892 + 166663 = 605555$ which is a little greater than the value we found as approximate, to be expected from the value of $c_2 | c_2$ determined from Hopfield's band system, namely, $604916 \pm$.

We have now located, by spectroscopic means, involving no calculations but additions and subtractions, the following molecular levels, which have been proven consistent with one another by calculations of levels to be expected from considerations based only upon sub-atomic dimensions.

$$\begin{array}{rcl}
 c_2 | & = & 605555 \text{ whence } c_2 = .4256 \\
 c_2 | c_2 & = & 151229 \text{ whence } c_2 = .4258 \\
 c_2'' | a_2 & = & 198307 \text{ whence } c_2'' = .4559 \\
 \text{or } c_2' | b_2 & & \text{whence } c_2' = .4456 \\
 b_2 | & = & 478021 \text{ whence } b_2 = .479 \\
 b_2' | & = & 463346 \text{ whence } b_2' = .4865 \\
 a_2 | & = & 438892 \text{ whence } a_2 = .4999
 \end{array}$$

Of these the level 478021 is the only one that is subject to serious doubt, which would be resolved, most probably, if the line is a band line, and not one due to a simple combination of only two levels. There are many possible combinations of atoms that might be expected, and which would give levels in the extreme ultraviolet, which have not been found because the lines have not been reported. It may be that the other combinations of atoms do not ordinarily occur in helium, or it may be that they will be observed in the future. Be this as it may, it will be found in succeeding chapters that we have not

exhausted our opportunities of obtaining the levels of combinations of sub-atoms 2 with one another, additional molecules composed of these sub-atoms being revealed by the various spectra of lithium, as well as other elements. We may summarize the information as to the dimensions of the sub-atoms obtained from the spectra of helium, as follows:

Of sub-element 1, a new dimension, not revealed by the hydrogen spectrum, $a_1' = 1.005 \pm$

Of sub-element 2 the following:

$$\begin{array}{lll}
 a_2 = .4999 & b_2 = .482 \pm & c_2 = .4222 \text{ to } .4292 \\
 & b_2' = .488 \pm & c_2' = .4456 \text{ to } .4470 \\
 & & c_2'' = .4525 \text{ to } .4560 \\
 & & c_2''' = .4626 \text{ to } .4646
 \end{array}$$

CHAPTER IX

LITHIUM

Lithium is the third element in the order of increasing atomic weights as well as of atomic numbers. Its atomic weight, as determined by chemical methods, is 6.94. By positive ray analysis it is shown to produce ions of weight 7 and also of weight 6. If truly isotopic, the atoms of weight 7 predominate, comprising, according to Aston, 94 percent of the total, leaving about 6 percent of mass 6. Thus, in the spectrum of ordinary helium, we should expect the most prominent lines to represent the spectrum attributable to lithium of mass 7, and we shall so consider these spectra in our discussion of spectral levels.

Lithium has been made to give off ions having a ratio of mass to charge of 2 to 1, by bombardment with hydrogen ions, at sufficiently high velocities. This implies that the particles have mass 4 and charge 2 or mass 2 and charge 1. The larger mass has been ascribed to them in the past, assuming them to be ionized atoms of helium that have lost two electrons. We, however, shall consider them as having mass 2 and charge 1, ionized sub-atoms 2. These bombardments have been investigated recently by Professor Lawrence.¹ If these particles have mass 4, and one is ejected, it would leave a unit of mass 3 to be accounted for, while if they are of mass 2 two of them would have to be removed to leave an atom of mass 3. We will show from the lithium spectra that these ions must be the same as we have already found, associated with hydrogen atoms, in helium.

The atomic volume of lithium is almost the same as that of hydrogen. Thus it seems unlikely that the lithium atom can contain an atom of hydrogen and something else; and it is very unlikely indeed that a lithium atom could contain two atoms of hydrogen. However, it is not impossible, if the element is truly isotopic, that the lighter atoms, of mass 6, may be somewhat larger than the others, and contain an atom of hydrogen each.

The chemical valence of lithium is 1. In the pure state, at ordi-

¹ *Science*, October 21, 1932.

nary temperatures, lithium is a metallic solid. It melts at $186^{\circ}\text{C}.$ and boils at $1400^{\circ}\text{C}.$, its vapor being said to be monatomic.

There are several distinct spectra emitted by lithium. Some of its salts, and the hydride, give band spectra, which we will not consider, as the spectra ascribed to the atom suffice for our present purpose, and the writer has not studied these band spectra. The various spectra ascribed to the atom give the levels that have been collected in Table 14, which gives also the quantum numbers and the molecules to which they are attributed, and such atomic radii as are derivable. What is called the normal spectrum is designated as Li I. It is usually attributed to the normal atom that has not lost any electrons. It is excited by heating a lithium salt in the Bunsen flame, or by using lithium salt on an electrode in a vacuum tube. If this spectrum can be excited in a vacuum tube containing no volatile material other than lithium, the writer has not found any account thereof. This spectrum resembles the parhelium spectrum in that there are four series of levels, as analyzed in the usual manner, the π series being doublets, but separated so slightly as to be scarcely comparable with the helium doublets. Fowler gives 6σ levels, 41 π levels, 7 δ levels and 2 φ levels. The δ and φ levels are almost identical with those similarly designated in helium, suggesting that they originate in the same molecules. In our table we consider only the first few terms, and accept Fowler's wave numbers as correct enough for our purpose, although they do not take account of creep.

The first enhanced spectrum, or Li II, has two systems,—one called a doublet system although the separation of the members is very small, and the other a singlet system. The wave numbers of the levels of the doublet system in our table are those given by Werner.² The levels of the singlet system are those of Sugiura.³

The second enhanced spectrum, designated as Li III has been measured in part by Erickson and Edlen.⁴ These same investigators have also reported two lines which they attribute to the regular spectrum of lithium, the levels of which are included in the table.

As indicated in the table, three sizes of sub-atoms contribute to the structures of the line molecules that produce these various spectra ascribed to lithium, namely, sub-atoms 1, 2 and 3. Each variety

² *Nature*, October 27, 1925.

³ *Journal de Physique*, (6), 6, 1925.

⁴ *Z. Physik.*, 59, 1930.

of sub-atom has several dimensions, or radii, which may lie in the axis of the molecule. Our hypothesis is that the normal lithium atom is composed of one sub-atom 3 and two sub-atoms 2, all held together by their charged parts, and that in lithium itself, except possibly the isotopic form of mass 6, which we are ignoring for the present, there is no hydrogen, or sub-atom 1. The spectrum ascribed to Li I, however, requires sub-element 1. These sub-atoms must be supplied by the salt, or gas in the bunsen flame, or present in the excitation tube, or by the isotopic form. The spectrum Li II, requires no hydrogen, but does require a liberal supply of sub-element 2, which is readily supplied by the normal lithium atoms upon division. The two spectra ascribed to Li III represent one system with molecules composed of sub-atoms 2 exclusively and another system with molecules of sub-atoms 3 exclusively.

Only in the levels of Li I and the regular series of Li III do we have evidences of sub-element 3. The other levels confirm and supplement the radii we found for sub-elements 1 and 2 in our study of helium. The new dimension of that atom is found in the P levels of Li II, where we have $a_2' = .5063$, which is not given by the helium spectrum just as the dimension a_1' is not found in hydrogen, but is found in the P levels of helium.

While the sub-atomic dimensions revealed in these spectra are substantially the same as revealed in helium, with the addition just noted, the combinations are different, as we might expect from the fact that the normal arrangements of the parts in lithium atoms cannot be the same as in helium.

The initial σ level in Li I is ascribed to the molecule $a_1c_3 | c_3$. It might equally well, perhaps better, be ascribed to $a_2c_3 | c_3a_2$ but the wave numbers alone do not give us the data required to determine which combination should be selected. The writer inclines to the alternative, rather than to the configuration indicated in the table.

We may summarize the new levels due to combinations of sub-atoms 2, not revealed to us in the helium spectrum, noting that, except in two cases where the dimensions are new, but not unlooked for, the dimensions of the sub-atoms are found to be substantially the same as from the helium spectrum.

$$\begin{array}{ll} c_2 | & = 610112 \text{ whence } c_2 = .4239 \text{ from } 1S \text{ of Li III} \\ c_2' | & = 546703 \text{ whence } c_2' = .4479 \text{ from } 1S \text{ of Li II} \end{array}$$

| | | | | | | | | | | | | |
|----------|-----|----------|-----|--------|--------|----------|-----|-------|------|----|----|--------|
| c_2'' | $ $ | c_2'' | $=$ | 134033 | whence | c_2'' | $=$ | .4523 | from | 2s | of | Li II |
| c_2''' | $ $ | c_2''' | $=$ | 125197 | whence | c_2''' | $=$ | .4680 | from | 2S | of | Li II |
| b_2' | $ $ | b_2' | $=$ | 115808 | whence | b_2' | $=$ | .4867 | from | 2p | of | Li II |
| a_2' | $ $ | a_2' | $=$ | 108262 | whence | a_2' | $=$ | .5003 | from | 2P | of | Li III |
| a_2'' | $ $ | a_2'' | $=$ | 106967 | whence | a_2'' | $=$ | .5063 | from | 2P | of | Li II |

The writer regards the level ascribed to $a_2' | a_2'$ as doubtful; the others as fairly certain, although they may be slightly misplaced owing to the methods of calculating the various series. He has not recalculated these series, but has taken them as given by those who discovered them. Only two dimensions of sub-element 3 are given by the lithium spectra, as thus far reported. These are $c_3 = .2941$ to $.2991$ and $a_3 = .3333$ (approximate). We might expect this sub-element to have several b dimensions and even more c dimensions, if we were guided by analogy alone; but we might also expect that these dimensions would not be revealed in the lithium spectrum if guided by what we have found as to the incomplete record of sub-element 2 in helium. Of course, the investigation of all spectra that may be emitted by lithium, or any of its breakdown products cannot be considered as absolutely complete; but we must look to the known spectra of other elements for further information about the dimensions of this sub-element, as well as for confirmation of the dimensions thus far found.

Before proceeding to examine the spectra of other elements, let us recur to the matter of possible isotopes of lithium. The evidence of positive ray analysis, alone, is not sufficient to prove that the atom is isotopic, for, there are many forms of line molecules that could be derived from lithium by excitation, which would have atomic weight 6. Any combination of two atoms of weight 3 or three atoms of weight 2 would produce a molecule that, with one electron missing, would behave as a projectile exactly as the supposed isotope. The isotope may be there, and its presence seems very likely because of the recorded atomic weight; but more evidence is requisite to prove this, if it be so.

CHAPTER X

BERYLLIUM

Beryllium is the fourth element in the order of increasing atomic weights as well as of atomic numbers. Its atomic weight, determined by its chemical combining properties, is 9.02, and by methods of positive ray analysis Aston has found but one isotope, of mass 9. Helium gas is found associated with some of the beryllium minerals, from which it is released by heating. It is thought that the gas is occluded in the minerals, and not in chemical combination; and its source is suspected to be radioactivity of the beryllium; but if this element is radioactive, in the same sense as radium is radioactive, it is only very slightly so.

The atomic volume of beryllium is somewhat less than one half that of lithium. From this fact it seems unlikely that the beryllium atom can contain more than one atom of sub-element 2, and from its X-ray spectra and atomic number it should contain an atom of sub-element 4. This leads us to suspect that the normal beryllium atom is constructed of three sub-atoms, one each of sub-elements 2, 3 and 4, giving a total of 9.

Pure beryllium is a metal, melting at 1280°C., boiling point unmeasured. Its chemical valence, with respect to hydrogen, is 2. Its ores are chiefly silicates, and it is comparatively rare, although not so rare as to preclude its being used for some industrial purposes suggested by its unique physical properties. At the present time its alloys are receiving considerable study.

In our scheme beryllium is regarded as a compound of the three sub-elements mentioned in the preceding paragraph, and we should expect its spectrum to reveal the sub-atoms of all three of them. Thus it is distinctly more complicated than either helium or lithium, and cannot be expected to break up in the same manner upon excitation.

In looking for series we should expect the quantum numbers in some series to increase by increments of 1 if sub-element 1 is present, in some series by increments of .5 if sub-element 2 is present, in some series by increments of .333 if sub-element 3 is present, and finally

in some series by increments of .25 if sub-element 4 is present, each series requiring its own conditions of excitation, implying not less than a certain critical potential for each. We shall follow the usual custom, and denote these different series by Be I, Be II, Be III and Be IV. The levels are given in Table 15.

When pure beryllium wires are used as electrodes in vacuo (the use of such electrodes of pure metal being impracticable with lithium, at least at present, on account of its low melting point, if not for other reasons), it is found not possible to excite the spectrum Be I, although Be II is excited under those circumstances. This indicates that sub-element 1 is not present in pure beryllium. However, various salts of beryllium are used to excite the spectrum ascribed to Be I, the other elements in the salts supplying the necessary hydrogen. This interpretation is radically different from that of the prevailing theories, which fail to account for the conditions required to excite the spectrum Be I from the metal in the pure state.

In exciting the spectrum of Be I so many other elements have been present in the excitation tubes that the investigators have been obliged to ascribe only some of the observed lines to this element, and to reject others, chiefly those known to be emitted by other elements when beryllium is not known to be present and is believed to be absent. Usually, the rejected lines are not published, and the student who desires to review the data with a view to placing some other interpretation upon them than that given by the original investigator finds himself somewhat handicapped, though he is relieved of the obligation to study carefully much material which undoubtedly is not necessary. Thus, the writer has not been able to satisfy himself fully concerning the conditions of excitation of spectra ascribed to Be I, and other spectra which are discussed somewhat in this book.

In Table 15 the known levels of beryllium, in its various states of aggregation, are given, with quantum numbers and other data such as have been set forth in the tables relating to other elements. We will discuss that ascribed to Be III first, because it is in some respects the simplest, and also because its upper level is obviously due to the *c* configuration of the sub-atom 3 which we have just found in the lithium spectrum. It would appear that this spectrum arises from recombinations of sub-atoms 3 derived from beryllium atoms that have been broken up completely by excitation. The values of a_3 derived from Edlen's levels are somewhat high. If we increase all of

his wave numbers by about 1400, which of course does not imply any change in the wave numbers of the lines, or their classifications, we get substantially the same value for c_3 and for a_3 about .3333.

Evidence of the presence of sub-element 4 is found if we accept Edlen's lines ascribed to Be IV. Unless improperly classified, they admit no other interpretation than that given in our table,—namely, as due to the a configuration of sub-atom 4. However, as only two lines were reported, we cannot consider these data as altogether sufficient.

The levels of Be II, as determined by Paschen and Kruger, who used beryllium wires in vacuo, apparently indicate combinations of sub-atoms 2 and 4, sub-atoms 3 not being in evidence in these series. The F and D series appear as separate levels only on account of creep. The values of c_4 and b_4 given in this table are of the right order of magnitude, to be expected by analogy, but of course a single determination of such a dimension, from a single series, does not amount to proof. The spectra Be II, Be III, and Be IV, taken together, if we accept the classifications of the lines made by the investigators, who were not guided by the writer's conceptions as to interpretation, indicate the presence of the three sub-elements, 2, 3 and 4. They all were obtained with the use of pure beryllium wires in vacuo, and the possibility of impurities being responsible for these lines is practically excluded.

Our table gives the principal levels of Be I according to Selwyn, who used Acheson graphite electrodes, with beryllium salts in cavities therein. The differences between the quantum numbers approximate unity, and although there is some irregularity, there are enough terms to make it certain that the progressions are real, and to establish the fact that these increments are due to hydrogen. As yet, the writer has not found these data sufficient for the analysis of the line molecules responsible for the initial levels, and for that reason has not set down suggestions as to these structures. Combinations of three sub-atoms, each having numerous different radii which may be in line, without knowledge of the radial dimensions possible in the smaller units, present too many possibilities and too many unknowns and make guessing, or the publication of what can be only guesses, unwise. It is believed that the future will reveal much more spectroscopic data bearing upon the structure of this element.

CHAPTER XI

BORON

Boron is the fifth element in the scale of increasing atomic weights and numbers, the third in the first of the two series of eight elements. Its atomic volume is somewhat less than that of beryllium, and about one third that of lithium or hydrogen. This suggests that boron contains no atoms of either sub-element 1 or 2, and that its prevailing form, if it be isotopic, is a combination of one atom of sub-element 5 with two of sub-element 3, making a total weight 11. The International atomic weight is 10.82. Aston reports isotopes of mass 10 and of mass 11, the latter predominating, as determined by positive ray analysis. There are two forms of pure boron, one crystalline, with a specific gravity of 2.54 and the other amorphous, with specific gravity 2.45. The melting point of the amorphous form is reported as being between 2000°C. and 2500°C. It sublimes at 3500°C.

If we rule out the presence of sub-element 1, which both the atomic volume and the character of the spectra seem to demand positively, and assume the possibility of two isotopic forms, each made up of sub-atoms which are not isotopic, there are the following possibilities of accounting for the atomic weights of the isotopes:

Atomic weight 11

$$5 + 3 + 3$$

$$5 + 4 + 2$$

Atomic weight 10

$$5 + 3 + 2$$

$$5 + 5$$

The combination $5 + 5$ could not represent a chemical atom, but it might possibly represent a line molecule formed by recombination of parts of dissociated atoms. It is only a very remote possibility that this could be the source of positive ions observed by Aston. We may feel assured that, unless some of the sub-atoms are isotopic, there are only three possible combinations of atomic structure,—two of mass 11 and one of mass 10. The form $5 + 4 + 2$ does not seem very probable, but if it is present there should be some spectroscopic evidence of it. It should be remarked that the international atomic weight, 10.82, has been influenced to some extent, by the finding of isotopes by Aston, the value ascribed to it before his work

being higher; and while the evidence that there are two forms of boron, of different masses, is strong, it does not as yet amount to proof.

The study of the spectra of boron has been difficult for several reasons. Pure boron has not been found suitable for electrodes, and the extremely high boiling point of the pure element renders it impracticable to supply the vapor alone to any form of excitation tube. Consequently, all spectra of boron that have been studied have been produced with salts of boron as the sources of the element within the tube. This makes the difficulties of eliminating all lines that might be due to impurities, or according to the writer's system, to sub-elements supplied by impurities, much greater than in the case of beryllium, where pure wires were used for the enhanced spectra, though not for the normal spectra, as the salt spectrum is called.

Table 16 gives the various levels of boron, with other data corresponding to that in our previous tables. The spectrum ascribed to B I is according to Selwyn, who used as electrodes the salt H_2BO_3 in cavities in carbon electrodes. The levels of the other spectra are from the work of Edlen, who used cored beryllium wires with B_2O_3 in the cavities. Edlen reported lines ascribable to H, Mg, Al, Si, Ca, Fe, Cu and Zn as recorded on the plates on long exposures, indicating that all of these elements were present as impurities. We must not forget such facts when attempting to account for the spectra attributed to boron, for there is the possibility that some of the lines rejected as due to impurities originate from combinations of the ingredients of boron atoms, and also the possibility that some levels ascribed to boron are due to combinations of sub-atoms of other origin.

In the case of beryllium we found it of advantage to discuss the enhanced spectrum first, and we will follow that course in considering the spectra of boron. B V is evidently the regular spectrum of sub-element 5. Only two levels are given, and these rely upon the interpretation of only one line, so that the evidence is rather scant. B IV is strictly analogous to Be III and gives us some confidence in the level c_4' which is larger than the value of c_4 we found from our scanty data in the beryllium spectra. Whatever its source, boron or one of the impurities, this spectrum shows the presence of sub-element 4 in an unmistakable manner, and if due to boron, favors the presence of the isotope designated $5 + 4 + 2$.

The evidence regarding sub-element 3 is clear in B III. Atoms of sub-element 3 alone contribute to this spectrum, and the progressions are well developed. The *D*, *E*, *F* and *G* series of levels of B III are mathematical only, there being but one series of molecules which act as physical causes of these levels, the differences being due to "creep." The progressions in B II are undoubtedly due to the presence of sub-element 2, but its origin cannot be attributed with any confidence to boron, because it is present in the beryllium, and also in the other elements in the salt. Similarly, the progressions in the levels of B I are undoubtedly due to hydrogen, but its source cannot be traced to boron.

It is much to be hoped that means will be found to investigate these, and perhaps other spectra derivable from boron, produced under conditions that will remove the doubts and obscurities which are inherent in the sources from which these spectra have been excited.

All of the levels interpreted in Table 16 are to be found in Bacher and Goudsmit's compilation "Atomic Energy States," published in 1932. The writer's work on this, and other spectra, was done largely before that work was available, and the data originally taken from the prior publications of the various physicists who made the investigations.

CHAPTER XII

CARBON

The sixth element, carbon, with its chemical valence of four, its capacity of combining with other elements in countless ways, its prominent part in the physical structure of all living organisms, excites our interest from whatever direction we may approach its study. Among the chemical elements it is unique in many of its attributes. Its atomic volume is the smallest of all chemical elements. It combines with the maximum number of atoms of hydrogen that may be attached directly to another single atom,—four. It has a number of solid forms, of which diamond is the densest, with a specific gravity of 3.51, this being one of the hardest of materials known, while another crystalline form, graphite, with a specific gravity of 2.25 is one of the softest. Charcoal, with specific gravity about 1.88 has enormous capacity of absorbing various kinds of gases, and of releasing them again, sometimes in a different state of aggregation, when heated. There are innumerable varieties, or grades of coke, lampblack, and other forms of carbon which are almost entirely of carbon, chemically speaking, though containing traces or small quantities of other materials. Carbon combines directly with most of the metals, especially the useful ones such as iron, and gives them qualities which they do not alone possess.

From the smallness of its atomic volume we would not expect the carbon atom to contain any particles of sub-elements 1 or 2. Its atomic weight does not suggest isotopes, and positive ray analysis indicates only the mass 12,—12 being the atomic weight as now accepted in the international scale. In our preliminary schedule we have ascribed to carbon a structure consisting of one sub-atom 6 and two sub-atoms 3. This makes the structure analogous to that of helium, the largest sub-atoms in the structure being of about twice the length and half the mass of the smaller; but the carbon atom differs from the helium atom in the complexity of the shapes of its sub-atoms, as well as in their smaller sizes.

The great and various combining capacity of carbon for hydrogen, oxygen, nitrogen, and in fact most of the elements, must be due in

large part to its structure, as well as to its shape, in connection with the sizes and shapes of other elements, in their ordinary forms, at the range of temperatures and pressures that occur on Earth, where most of our experiments are made. The structure of the carbon atom therefore is of the greatest interest to us, as adequate knowledge of it would pave the way to a better interpretation of other elements which are not so outstanding in the universality of their applications or usefulness, from a human point of view, with all of its limitations.

Table 17 gives the known levels of carbon, ascribed to the different stages of ionization in the usual manner. It does not include any of the numerous band spectra of gases containing carbon, some of which are observed in nebular spectra, and the spectra of comets, as well as in the laboratory, thus indicating to us that something associated with carbon, oxygen and nitrogen also is widely distributed in the stellar universe. Much work has been done on these spectra of gaseous carbon compounds, and it all is of intense interest. But we omit all discussion of such spectra as beyond our present purpose.

However, it is not practicable for us to limit this discussion to spectra emitted by electrodes of pure carbon in tubes containing no gases other than carbon, for this would eliminate entirely the spectra C I and C II. Pure carbon electrodes, without any occluded gases or other impurities are very difficult, if not impossible to procure. When working with carbon electrodes in vacuo it is necessary to operate the tubes for considerable periods, at as high temperature as practicable, to reduce the gases (by continually exhausting them by pumping) exuded by the electrodes, if other elements than carbon are to be considered even approximately eliminated. There is every indication that, if the gases were eliminated entirely, pure carbon could not be forced to emit those spectra designated C I and C II. Therefore, when it is desired to examine these spectra, it has been found advantageous to introduce into the tube, and to continuously circulate through it, though at very low pressure, helium gas.

Hitherto the use of helium gas has been thought to produce conditions favoring the emission of these spectra by the carbon atoms. We take a very different view, which is, that the helium supplies an adequate and continuous supply of the sub-atoms 1 and 2 necessary to provide the progressions of the series ascribed to C I and C II. While the progressions in the quantum numbers of C I, or at least a part of it, are sufficiently regular to assure us that the series as classi-

fied are substantially correct, the data are not sufficient to enable us to determine with confidence, the configurations of the molecules which are responsible for the upper levels. However, it is quite clear that the lower levels may be ascribed to combinations of sub-atoms 3 with sub-atoms 1, or at least that many of them may be so ascribed. To make this clear, the levels of C I have been arranged in our table, not in the order of the series as given by Paschen and Kruger, but in a manner to indicate another relationship, by which a possible structure is indicated for the various systems,—this structure using the same sub-atomic dimensions that we have found in previous chapters.

There are similar difficulties in interpreting the spectrum ascribed to C II, which also is obtained by the use of helium, and occurs superimposed upon the spectrum ascribed to C I; but the part played by the helium in supplying sub-element 2, and the presence of sub-element 3 are sufficiently clear. The fact that helium supplies the possibility of exciting both of these carbon spectra with carbon electrodes, increases our confidence that our analysis of the structure of the helium atom was correct, as well as justifies our belief that carbon contains sub-element 3 and not sub-elements 1 or 2.

It has been remarked that there is an analogy between the structure of carbon and that of helium. From this, we should expect some similarity between the normal spectrum of helium, which has two, apparently independent systems, and the spectrum of C III. That there is such analogy the table bears evidence. The spectrum ascribed to C III is very complicated, and quite extensive. The progressions are by increments of .333 where the initial molecules are symmetrical, and are irregular where the initial molecules are not symmetrical. I have refrained from ascribing sources to the initial levels, except in a few instances. Part of each system contains some "normal" terms, that is, terms for which the quantum numbers are directly indicative of total lengths, and some "displaced" terms. The quantum numbers of the displaced terms are determined from the wave numbers given in the table plus the number 64591.3 which is the amount of the displacement, as determined by Edlen. That there may be such displaced series has been pointed out in our preliminary theoretical chapter. A very perfect example of such displaced series is found in the spectrum of Neon, to which we will come in a later chapter.

The spectrum assigned by Edlen to C IV admits of only one interpretation, so far as the writer is able to judge. It must be assigned to combinations of sub-element No. 4; and the levels Edlen has ascribed to C V must be ascribed to sub-element No. 5. Neither of these assignments is in harmony with the ascription of these spectra to carbon if carbon has the structure which the writer has assigned to it, which contains no sub-elements of numbers 5 or 4. The spectrum ascribed to C V is represented by a single line, and the evidence is slim that the line is properly assigned to the two levels selected, which, however, are reasonable, if the lower level is properly assumed. It seems most likely that this line is due to the combination set forth in the table, but is due to some impurity containing the sub-element 5, in the carbon electrodes, derived from some heavier element.

At the present time, the writer inclines to the opinion that the spectrum ascribed to C IV also is due to impurities. It may be possible, however, that there is an isotopic form of carbon containing one atom of sub-element 4. At the present time there is not available to the writer the data necessary to resolve this matter.

It is obvious to the reader that the present writer makes no pretensions to having attained a complete or satisfactory explanation of the spectra assigned to carbon. He has devoted only a few months to these spectra, and even if the data were entirely complete a much longer period of study would be required. It is not thought to be a reflection upon those who have provided the extant data for him to state that, in spite of the work that has been accomplished, more needs to be done upon these spectra before a fuller interpretation ought to be undertaken.

CHAPTER XIII

NITROGEN, OXYGEN AND FLUORINE

Nitrogen is the seventh element in the order of atomic numbers. Its atomic weight is 14.008. It solidifies at low temperatures, the melting point being -210.5°C . and its boiling point -195°C . The normal gas molecule is diatomic. With carbon, oxygen and hydrogen it is one of the chief elements in the bodies of living organisms.

The atomic volume of nitrogen is much greater than that of carbon,—in fact, almost as great as a carbon atom and a hydrogen atom combined. Its chemical valence, with respect to hydrogen, however, is 3, while that of carbon is 4. This suggests the thought that nitrogen is somewhat like carbon, with an atom of hydrogen combined with it in a manner more permanent than an ordinary chemical compound. Evidently, some change takes place in the scheme of atomic structure which results in both loss of hydrogen combining capacity and increase in size, which is the reverse of what takes place from lithium to carbon.

Aston, by methods of positive ray analysis, finds atoms of mass 14 only. However, if hydrogen is isotopic, nitrogen may be isotopic for the same reason, some of the nitrogen having the hydrogen atom of mass 1, and a total mass of 14 and about one atom in five thousand having a hydrogen atom of mass 2 and a total mass of 15. The atomic weight of 14.008 suggests that the hydrogen atoms in nitrogen have the same atomic weight as in hydrogen, and if one element is isotopic, so is the other.

Another reason for suspecting that nitrogen contains hydrogen atoms in its atoms is the fact that upon bombardment by alpha particles nitrogen has been found to emit hydrogen atoms or ions. Another evidence is that nitrogen alone gives an elaborate band spectrum, which carbon, beryllium and lithium do not, but hydrogen and helium do.

The combination of sub-atoms which appears to the writer most likely to comprise the normal molecule of nitrogen is one sub-atom 7, two sub-atoms 3 and one sub-atom 1; total mass 14. Thus, ammonia, NH_3 contains exactly the same total amount of hydrogen as

marsh gas, CH_4 , though the atoms are not given up with equal readiness.

It is obvious that, having one more sub-atom in its structure than carbon, the breaking up of the nitrogen atom will take place in different stages from the breaking up of the carbon atom; and we may expect to find the elucidation of the structure by its spectra more difficult, and the spectra more complicated. Such, indeed, is the fact; and although it is not difficult to obtain nitrogen in considerable purity, the analysis of its spectra is very difficult, and has only been accomplished in part, much information regarding it being in a controversial stage.

Oxygen is the next element in the atomic scale. Its atomic weight, 16, is taken as the standard for measuring the atomic weights of other elements.

Until very recently there was no convincing evidence that oxygen is isotopic, but assertions are now made that while most oxygen atoms are of mass 16 there are forms of the atom which have mass 17 and mass 18, though these forms are considered to be very few in number in comparison with the others. There is no doubt now that, in ordinary water there are molecules different from the ordinary water molecules, and that these can be concentrated into what is called "heavy water." Hydrogen, produced electrolytically from such water gives a spectrum in which appear, in addition to the ordinary Lyman lines, other lines, similarly arranged in series, but shifted slightly toward the region of higher frequency. Whether these are due to isotopic hydrogen or to some other cause was left undiscussed for the present, in our chapter on hydrogen, for reasons there stated.

The question whether or not oxygen is isotopic is very closely allied to the question of hydrogen isotopes, and will not be discussed here except to say that, in case oxygen is isotopic, the heavier forms must be very much rarer than the heavy hydrogen atoms, and far too few to have any observable effect upon the ordinary spectrum of "pure" oxygen prepared by ordinary methods.

The oxygen molecule is diatomic, as is that of nitrogen. The melting point is -218°C . and the boiling point -182.7°C . There is a triatomic form, known as ozone, but it is not as stable as the diatomic form.

The valence of oxygen with respect to hydrogen is 2, less than nitrogen, which is 3; but the atomic volume, instead of being greater,

is less than that of nitrogen, though considerably greater than that of carbon. These facts seem to be at least partially accounted for if we ascribe to oxygen a structure composed of one sub-atom 8, two sub-atoms 3, to which is added one sub-atom 2, making a total mass 16.

Although much study has been given to the spectra of oxygen, the results are not such, as yet, to make it profitable to give the levels and their quantum numbers here. The spectrum O I either cannot be excited at all, or is very weak, if pure oxygen is used in the excitation tube, and all sources of hydrogen, atomic or subatomic, avoided. It may be excited when other gases are present, and especially in the presence of helium. The spectrum of O II is excited in pure oxygen without the aid of helium. The other enhanced spectra of oxygen have not been fully observed nor fully analyzed, and in consequence we have no spectroscopic knowledge regarding the dimensions of the sub-atom 8 except that derived from X-ray spectra, which will be dealt with in a later chapter.

Fluorine, ninth in the atomic series, occurs as a diatomic gas, with atoms of mass 19. The melting point is -223°C . and the boiling point -187°C . The atomic volume is about fifty percent greater than that of oxygen, or twenty percent greater than that of hydrogen. The various spectra of fluorine have not yet yielded to analysis sufficiently to make it possible to determine the structures of the line molecules which are responsible for the levels. When more data are available it will be possible to resolve these structures with assurance. At the present time, the structure thought most probable by the writer is one sub-atom of sub-element 9, two of sub-element 3 and two of sub-element 2.

According to our scheme as thus far outlined, the smallest number of sub-atoms is required in the atoms of smallest atomic number. As the atomic number increases, the number of sub-atoms increases, but not regularly. It is the aggregation of sub-atoms, not the one which is responsible for the atomic number, that determines both the total size and shape and the valence. A full understanding of valence depends upon our understanding the arrangement of the subatoms in the normal atom; it does not depend upon the inner structure of the sub-atoms except in so far as that may determine the general arrangement. A study of the grosser features of the structure of the chemical atoms does not require us to begin with a study of the inner structure of the sub-atoms, or their nuclei. Rather, it has been

hindered hitherto by failure to recognize that the nuclei belong to sub-atoms, and not to chemical atoms as final units. Only when the grosser structure of atoms is fully understood can we hope to possess data enough to elucidate the inner structure satisfactorily, and to ascertain its relationship with the ether, or other medium, which transmits electromagnetic vibrations.

CHAPTER XIV

NEON

Neon, atomic number 10, chemical valence 0, is the second of the "inert" elements, helium being regarded as the first. Its atomic volume is slightly greater than that of nitrogen, or about twenty percent greater than that of hydrogen, and its atomic weight is 20.2. It is not altogether without capacity of combining its atoms, for it can be liquified and frozen, its melting point being $-253^{\circ}\text{C}.$ and its boiling point $-239^{\circ}\text{C}.$ —both higher than the corresponding critical temperatures of hydrogen. Neon is present in the atmosphere in small proportion to other gases, and it is recovered therefrom for industrial purposes, by freezing out the more plentiful constituents. Its chief use in industry is in the manufacture of neon lamps, an unusually large proportion of its radiation under ordinary excitation being within the range of frequencies of visible light.

By positive ray analysis Aston finds neon to be isotopic, the positive ions produced in it having masses 20 and 22. However, so far as the writer is aware, no concentrations of the supposed isotopes have as yet been produced, and the explanation of these two positive ions must rest, as yet, partly upon theory. If there actually are two forms of neon atoms in ordinary neon, of masses 20 and 22, in view of the fact that the atomic volume is only a little greater than that of hydrogen, it is impossible that the lighter isotope contain more than one atom of hydrogen, or sub-element No. 1.

That hydrogen is present in ordinary neon cannot be doubted, because this element produces, upon excitation, a very extensive arc spectrum. The analysis of this spectrum is one of the many outstanding achievements of Paschen, who found 16 series of levels that progress in such a manner that their quantum numbers increase by increments of approximately 1, and ten series of "displaced" levels, whose quantum numbers, after allowing for displacement, increase by increments of 1. The displacements are of the character anticipated in our theoretical chapter, and indicated by Series D in Table 4.

Consideration of these quantum numbers indicate that the progressions all are due to the addition of a hydrogen atom to the appro-

prate end of the line of a line molecule, and that the leading or initial levels of each series of levels may be accounted for as follows: The initial level of four of the series,—two normal and two displaced,—originate in line molecules having six sub-atoms No. 3 in line. The initial levels of ten series,—six normal and four displaced,—originate in line molecules having four sub-atoms No. 3 and two No. 2 in line. The initial levels of twelve series,—eight normal and four displaced,—originate in molecules having four atoms No. 3 and four atoms No. 2 in line. The data do not suffice for determination of the precise arrangement in any case, and as the spectrum of Ne I is very extensive, it is not included in our tables.

An enhanced spectrum ascribed to Ne II has been observed, and the lines classified by Russell, Compton and Boyce, who estimated the "lowest state" as $\nu = 330429$. Quantum numbers computed on this basis give so few progressions separated by intervals of .5, such as are usual in enhanced spectra of this order, that the writer, while accepting the classifications of the levels as probably correct, does not feel that the initial level is justified. In place of it he has taken $\nu = 293763$, and computed the other levels accordingly. The wave numbers so computed, with their quantum numbers, are set down in Table 18. These quantum numbers are capable of being interpreted as due to combinations of sub-atoms 3 only. The table is merely a suggestion, no full interpretation being possible with the information at present available.

With these suggestions offered by the spectra, incomplete as they are, the atomic weights found by Aston might be accounted for as due to ions made up of the following combinations of sub-elements, each combination lacking one electron, there being several alternatives.

| | |
|-------------------------------|-----------------------------------|
| $20 = 10 + 3 + 3 + 3 + 1$ | $22 = 10 + 3 + 3 + 3 + 3$ |
| $20 = 10 + 3 + 3 + 2 + 2$ | $22 = 10 + 3 + 3 + 3 + 2 + 1$ |
| $20 = 10 + 3 + 2 + 2 + 2 + 1$ | $22 = 10 + 3 + 3 + 2 + 2 + 1 + 1$ |
| | $22 = 10 + 3 + 3 + 2 + 2 + 2$ |

It is possible, in so far as mere numbers contribute evidence, that the atomic weights could be accounted for by the inclusion of some sub-element heavier than No. 3 and lighter than No. 10; but we find no evidence of such sub-element in the spectra examined, and knowledge

of more enhanced spectra of neon is too imperfect to afford us any suggestions at the present time.

The next element after neon in the scale of atomic numbers is sodium. Its atomic volume is almost twice that of hydrogen, and it develops an ample arc spectrum. Its chemical valence is 1. From its X-ray spectra, considered briefly in the following chapter, we ascribe to it one unit of sub-element 11. The sum of the masses required to bring the total mass up to 23, from 11, is 12. Sodium is not known to be isotopic. It is evident, therefore, whatever the structure of sodium may be, it contains more of the lighter sub-elements than neon, and there is some change in the scheme of atomic structure which takes place in passing from neon to sodium. On account of this increasing complexity, probably involving an increasing number of sub-elements in the structure, as well as sub-elements smaller and heavier than No. 3, we will not attempt to analyze the spectra of elements heavier than neon, with a view to ascertaining sub-atomic dimensions, at this time, but will turn our attention to X-ray spectra, in the hope that therein we may find evidence concerning the shapes and sizes of sub-atoms heavier than No. 3, more directly available than in arc or spark spectra.

CHAPTER XV

X-RAY SPECTRA

When any chemical element is subjected to bombardment by electrons which have been accelerated by falling through a sufficiently high voltage, or subjected to X-rays of sufficiently high frequency, it emits non-characteristic X-rays which give a continuous spectrum, the upper limit of which cannot exceed a limit fixed by the voltage, or the upper frequency of the X-rays used in excitation. In addition to such non-characteristic radiation each chemical element so excited may emit characteristic spectra, called X-ray spectra, if the voltage or excitation frequencies are high enough, in addition to the enhanced spectra,—that is, spectra due to recombinations of parts of atoms that have been partly broken up,—some of which have been discussed in previous chapters, which, for the most part, are excited by voltages much less than those required for X-ray spectra of the heavier elements, especially the *K* lines thereof.

There are several systems of X-ray spectra, each consisting of groups of lines as well as continuous spectra, the lines of highest frequencies for each element being known as the *K* series, those of the next highest as *L* series, and those of still lower frequencies as the *M* series, and so on. The most complete account of X-ray spectra now available is contained in Siegbahn's "Spectroscopie der Röntgenstrahlen," second edition, 1931. The first edition of this work was published in 1923. It was translated into English by Professor Lindsay, and published in 1925. The second edition, however, contains much valuable data not available when the first edition was published. All numerical data used in this chapter are taken from the edition of 1931.

The *K* radiations comprise both continuous and line spectra, the continuous spectra containing by far the greater part of the energy, as evidenced by photographic records. The *K* lines of each element vary greatly in intensity, and greater numbers of them are observable as greater perfection in methods of excitation and measurement are devised. The most intense *K* line for each element is designated K_{α_1} . It is accompanied by another line, K_{α_2} the two forming a doublet

so close as not to be distinguished by methods now in use, when arising from elements of lower atomic weight than sulphur, but very considerably separated in the spectra of elements near to the other end of the periodic table. The separation increases regularly, but at a rate much greater than the increase in frequency in K lines from element to element.

The next in intensity and regularity of K lines are designated K_{β_1} and K_{β_2} . These have been measured for most of the elements higher in the periodic scale than nickel. However, there have been quite a number of K lines measured for the lighter elements, which do not belong to the regularly progressing series of alpha and beta lines, in some cases as many as 12 such lines having been found for a single element, and it seems likely that many lines corresponding to these may be found for other elements when methods of investigation have been developed.

In previous chapters we have seen that each of the lighter elements gives rise to several systems of spectra, characterized by series, usually ascribed to several stages of ionization, hydrogen alone having but one such system. The series limit of the hydrogen system is $N = 109678$ (approximate). That of helium, ascribed to He II is 4×109723 (approximate). Other spectra, as we have seen, introduce characteristic numbers $3N$, $4N$, and so on; but unfortunately our measurements of enhanced spectra, and our analyses thereof, are not yet sufficiently accurate to enable us to obtain values of N from enhanced spectra for any except the four or five lightest elements, and for these the determinations, except in the case of hydrogen and helium, are not sufficiently precise to be used for predicting what the corresponding series limit ought to be for heavier elements, by any process of extrapolation, based upon observation alone. The Quantum Theory, however, from theoretical considerations which need not be discussed in this connection, has adopted a value of the absolute, or "theoretical" Rydberg number, $N = 109737$, which is taken as a unit in comparing X-ray spectra. X-ray lines, instead of being given in wave numbers, are usually given in terms of $\nu \div N$, and may be reduced to wave numbers by multiplying the numbers given in the tables by this number, 109737. As this number does not differ very greatly from the Rydberg number for hydrogen, we would not be greatly in error if we ignore slight discrepancies in the calculation of levels of X-ray spectra such as might arise from slight differences in

the value ascribed to the Rydberg number by various investigators, in making their calculations.

When the corresponding K lines of X-ray spectra expressed in $\nu \div N$ are arranged in the sequence of their atomic numbers, they comprise a mathematical series. This is readily seen by comparing the square roots of these numbers, and their differences, set forth in Table 19, for the leading K lines only. It appears highly probable that all of the K lines of each element correspond to K lines of other elements in a similar manner.

The L lines are much more numerous than the K lines, and have much lower frequencies, and the M , N and other series have still lower frequencies. All of them, however, can be arranged in regular series progressing from element to element, although the lightest elements give K series only, those somewhat heavier both K and L series, and only the heaviest elements all the known series of lines. We wish to point out emphatically that all of these series, taken from element to element, manifest considerable regularity, the higher series (frequency considered) being the more regular.

The writer believes that these lines are due to the separation from the atoms to which the atomic numbers are ascribed of the sub-atoms which are responsible for the atomic number, and the recombination of these sub-atoms to form line molecules containing sub-atoms of one variety only, although arranged in different alignments in the line molecules which produce the levels between which these X-ray lines are arithmetical differences. The lines progress regularly because the changes in the dimensions of the sub-atoms progress regularly, and also because only one kind of sub-atom is concerned in each group of lines ascribed to the same element.

If this hypothesis be tenable, it requires that, incidental to, or prior to, the process of excitation, these sub-atoms must be separated from the chemical atoms, so that they may combine with one another to produce line molecules containing the one kind of sub-atom only. Unfortunately our knowledge of X-ray spectra of the lightest elements is very incomplete, and our knowledge of enhanced spectra of heavier elements for which both K and L spectra are known is entirely lacking. Eventually, doubtless, these two fields of knowledge will overlap, and it will be possible to interpret series spectra in terms of X-ray spectra without having to span the gap by theoretical considerations based upon assumptions. On the other hand, it is for-

tunate that means has been found to extend the observations of K lines below the limit given in Table 19, far enough to include beryllium, although not as yet to include lithium or helium. Those who wish to look up the authorities will find references to them in the later edition of Siegbahn's book. Table 20 gives the K lines from beryllium to silicon, the observations on the lighter elements having been made by Solderman in 1929.

Conjecturing that these lines, for each element, are due to the combination of levels represented by $x \mid - x \mid a$, where x and a represent radii of the sub-element responsible for the level, and assuming that the longer radius, a , is proportional to the inverse of the atomic number, which means that the Rydberg number ought to be the same for all elements, we get values of the radius, x , which are obviously comparable with the values of c found from considering the series spectra of the lighter elements.

Enlarging on this suggestion, we may surmise that the K lines are all due to combinations of the types:

$$\begin{aligned} K_{\alpha_1} &= a \mid - c \mid a \\ K_{\alpha_2} &= a' \mid - c \mid a \\ K_{\beta_1} &= a \mid - c' \mid a \\ K_{\beta_2} &= a \mid - c'' \mid a \end{aligned}$$

To verify this, and to find the correct combinations if the suggestion is sound, will be a matter of considerable difficulty, for we know that the Rydberg number is not constant since we do not find it the same for the two lightest elements, hydrogen and helium, for which only it is known with any approach to precision. The theoretical Rydberg number is calculated on the assumption that the mass of helium is 4, while we have found that the mass of sub-element 2 most probably is 2. On the whole, it appears likely, that the Rydberg number increases much more rapidly from sub-element to sub-element than it has been assumed to increase, and that the number 109737 is merely an arbitrary constant, having no real significance. Ignoring theory and considering the matter from the observational side, we do not know the relation of c to a and cannot obtain it from K series alone. If the data were sufficiently precise, which it is not at present, we might obtain accurate values of a for the elements of light weight only, from enhanced spectra. We might also be able to calculate values

of a from X-ray spectra if we knew both K and L lines for the lightest elements, which we do not now know. It seems that we are, for the present, stopped from any further profitable computations of the value of a for elements heavier than helium by the lack of experimental data.

For each element the X-ray spectrum resembles in certain respects the optical spectra excited by lower voltages. Thus, the K lines comprise a group analogous to the Lyman series in hydrogen, and the L lines a group analogous to the Balmer series, and so on. Acting on this idea, those who have studied X-ray spectra have classified all of the known lines and computed levels between which the lines are differences. If the classification in such a table is correct, the actual levels are all arithmetical differences between one assumed upper level and certain rather accurately known departures therefrom. If the upper level is correct, the others are correct also. Therefore it is of the utmost importance that the upper level shall be correctly taken.

According to the hypothesis that has been suggested by the writer, the upper level of the X-ray series is that produced by the sub-atom in its $a |$ configuration, of which there may be doublets. If the Rydberg number were the same for all elements, the upper K level as expressed by $\left(\frac{\nu}{N}\right)^{\frac{1}{2}}$ would give the atomic number. According to the scheme outlined by Siegbahn this tallies well with the K level of the heaviest element, uranium, but gives 9.79 instead of about 12 for magnesium, and is not in accord for any of the lighter elements. The reason for this lack of correspondence seems to be that the upper levels taken for the lighter elements by Siegbahn and his associates were derived from the excitation potentials (in emission or absorption) and not from sub-atomic ionization potentials, which are higher, and not separately observed by means at our disposal.

To make this comparison complete, let us compare the following figures. The levels assigned to magnesium by Siegbahn are as follows:

In terms of $\frac{\nu}{N}$

$$K = 96.0 \qquad L = 3.7 \qquad M = .5$$

According to our hypothesis these should be increased to about:

$$K = 144 \qquad L = 51.7 \qquad M = 48.5$$

The differences are the same in both cases, but the upper level in the second schedule is more in line with what we should expect, although the upper level, $K = 144$ may even be a little low.

The conditions required for the excitation of X-ray spectra appear to be different from those to which we are accustomed in our studies of excitation of line spectra in gases. As is well known, it requires a potential of almost 16 volts to excite the spectrum of hydrogen if we begin with the gas in the ordinary molecular form; but when the spectrum has become established, 13.5 volts is able to maintain all of the primary lines. If only the first Lyman line is maintained, a potential of only 10.15 volts suffices, provided that the conditions are such that atomic hydrogen is maintained in the tube, by maintaining the temperature, or the current density. In X-ray spectra, however, it appears generally true that the K lines can be excited at the resonance potentials, and do not require higher potentials to prepare the atoms and produce the molecules necessary for the emission of the more prominent lines.

There is even a greater difference than this, if the data are correct as reported by the investigators. Not only may the K lines be excited at their resonance potentials, but the L lines also may be so excited. The Balmer lines of hydrogen, as is well known, can not be excited at potentials lower than those necessary to excite the corresponding Lyman lines in the ultraviolet. It thus appears that, if our system is in principle correct, the chemical atoms must have been broken up and their parts recombined to produce such molecules as $c | a$ of the atomic number of the element in question, before the excitation takes place in the molecules which are responsible for the lines. It seems that either the excitation necessary to disrupt the atoms must be very much less than that necessary to excite the recombined parts, or that the atoms are disrupted by something other than the radiation used for excitation. It might even be that the atoms are disrupted not by the action of radiation upon their electrons, but by the action of light in throwing into vibration, directly, their positive sub-atoms. This also may explain why the L levels are not readily excited, if excited directly at all, in the elements lighter than copper. There still are too many unknowns about X-ray spectra to enable us to solve these puzzles now; but we may hope that the future will provide the experiments by means of which they may be solved.

CHAPTER XVI

COSMIC PROBLEMS

Whether the system briefly outlined in the preceding chapters or some such system based upon mechanical laws, will be extended to account satisfactorily for all of the chemical elements is for the future to decide. The writer has not hoped to do more than show that this approach to the problem of the structure is promising, and ought to be followed by others. If the work of extension were limited to the interpretation of spectra the work required for complete development or disproof of the scheme as a whole would be vast, but even if that feat were accomplished, our system would still require ninety two sub-elements to produce the X-ray spectra now attributed to the ninety two chemical elements. The system suggested is a step toward greater simplicity, but does not of itself include solution of inner, or nuclear structure. It may indicate why the chemical elements are coherent, and what we should expect them to produce when broken up, but it does not, of itself give us insight into any process by which sub-atoms may be formed out of something finer or more subtle, or dissolved into the parts of which they, in their turn, are composed.

But even without a theory relating to the structure of the sub-elements, which the writer believes will prove attainable, the theory which we have outlined for the lighter elements, extended to apply to heavier elements, lends itself very well to intelligible explanation of some of the cosmic problems. For instance, astrophysicists tell us that there are stars, the densities of which as calculated from legitimate physical measurements are many times as great as the density of any chemical element known to man. While, at the surface of the Earth, the sub-elements are known to us only as parts of chemical atoms, we have no warrant for assuming that in the interior of all of the stars the conditions are such that these combinations prevail. If, in a massive star all sub-elements were present, and the temperature were so high that the sub-elements remained separate from one another, the heavier ones would tend to concentrate at the center, and the lighter and more bulky ones to work outward. If the temperature were high enough, the radiation pressure at the surface might be sufficient to expel the lighter sub-elements completely.

Since the volumes of the sub-atoms are approximately proportional to the cubes of their radii, and according to our schedule the radii are at least approximately proportional to the inverse of the atomic numbers, while the weights are directly proportional to the atomic numbers, the mean densities must be approximately proportional to the fourth powers of the atomic numbers. On this basis the mean density of sub-element 2 is 16 times that of sub-element 1, or hydrogen. Liquid hydrogen weighs $4\frac{1}{2}$ pounds per cubic foot. Liquid sub-element 92 would therefore weigh about 71,369,296 times as much, or 161,188 tons per cubic foot, or about 700,000 times as much as iron. A star full of such stuff would be rather heavy, and we have no warrant for assuming that, cosmically, 92 is the heaviest sub-element possible, for we do not know what renders this element unstable under terrestrial conditions, and so radioactive.

There is another kind of phenomenon now receiving much study, to which but little reference has been made in the chapters of this book. It is the ejection of massive particles from atoms subjected to bombardment by other atoms and ions moving at very great velocities. It is fairly obvious that a chemical atom, if composite, when struck by a very rapidly moving massive particle, might be shattered into its component sub-atoms, any one of which might be accompanied by its electron or might be deprived of its electron by the shock. The theoretical possibility of neutral sub-atoms as well as of ions of various atomic weights corresponding to the atomic numbers of the sub-elements is inherent in the scheme proposed.

It is also conceivable that such particles might be produced in Nature and be in part responsible for cosmic rays, as well as for various phenomena produced in laboratory experiments. There is no reason to disregard the point of view here suggested as to the structure of the elements as a-priori incapable of interpreting such phenomena as these, to which the writer has not attempted to apply this theory in a quantitative way.

The scheme proposed has an important bearing upon the problem of radioactivity. It suggests that in those cases where positive ions or massive neutral particles are driven out by bombardment by other massive particles,—charged or neutral, the expelled particles are sub-atoms or sub-atomic ions, and not parts of a central nucleus. Such expulsion may be the direct result of mechanical impact, similar to that of one billiard ball upon another. The emission of particles by

radioactive elements, however, appears to be caused by reactions of a different kind. The opinion commonly held is that both the massive particles that are expelled and the energy which causes their expulsion come from the nuclear structure. This scheme, however, suggests that the massive particles may be ions of the lighter sub-elements, not parts of the heavier nucleus, though the energy producing the expulsion may be derived from change in the sub-atom of highest atomic number. If the alpha particles expelled are ions of sub-element 2, as has been suggested, the schedules of atomic changes that have been drawn up to explain the changes in atoms in passing from uranium and thorium to lead, which have assumed that the mass of the alpha particle is 4 and its charge $2e$ will require critical revision.

In presenting the discussion of atomic structure and atomic shape the writer has purposely avoided the subject of the distribution of the charge within the sub-atomic ions, believing that study of this, which may be expected to throw light upon the inner structures, had better follow, rather than accompany, the study of size, form and arrangement of the sub-atoms. The data which have been studied have enabled us to ascertain, roughly, the atomic dimensions of only the three lightest sub-elements. A more accurate determination of dimensions would have to take into account the distribution of the internal charges, and the deformations due to pressures occasioned by the electrical forces which hold the various configurations together. If the masses of sub-atoms increase regularly with increasing atomic number, and the sizes decrease at the same time, it seems likely that the heavier sub-atoms must be composed in large part, if not entirely, of multiples of some unit which occurs singly in the hydrogen atom of mass 1. Therefore the diminution in size must depend in some way upon the arrangement of these units, which must be exceedingly small. To the writer this seems possible, without any abrogation of any mechanical laws or principles; and but a development along such lines is entirely outside of the limits which have been set for this book. It will require a workable model of ether structure, considering the ether as an ultra gas, with molecular structure, from which the nuclei of sub-atoms are produced by a process originating in ionization of the ether atoms themselves. The writer believes that before the human intellect has run its course we will recognize in the mechanism of the Cosmos only two kinds of physically ultimate "particles," or ultra-atoms, one possessing an inherently positive charge and the other

an inherently negative charge, both possessing definite mass, of which particles the ether itself, as well as all other forms of matter are composed.

The distribution of the ether in space is a matter to be investigated, not to be settled by any postulate, as by assuming a uniform velocity of light throughout all space. Shifts of spectral lines in distant nebulae from their positions here may be due to differences in the sizes of sub-atoms in those distant places from their sizes here owing to differences in ether density and pressure, as well as to proper motions of distant bodies owing to expansion of the universe as a whole.

If we entertain such an idea of ether structure it is possible to approach a study of it by means of ideal models, in a manner similar to that used in our chapter on ideal atoms. The writer has made attempts to account for the electromagnetic properties of the ether as natural to a gas composed of atoms, each compounded of one positive and one negative particle, in linear relationship to one another, considering the kinds of motion which would be set up in the atoms themselves as a result of their motions, otherwise helter-skelter, when subjected to electrostatic fields, both static and in motion. It does not seem to him impossible that a sufficiently competent mathematician could derive Maxwell's electromagnetic equations from such an ideal system of particles.

If such an ether gas be possible, and if the atoms of the chemical elements could arise within it by a process in which ionization plays a leading part, though each ether atom would possess inertia, and obey the laws of motion, it would not of necessity be affected by gravitational attraction. Gravitational attraction, in such a system might well be derivative, and due to the presence of the ether, or rather to the impact of ether particles upon matter in its more compact form.

Let us assume that the ether atoms are very small in comparison with their distance apart, and that they are moving helter skelter, with velocities which are very high, so that the average distance traversed between collisions is vast. A collision between two ether atoms, though of rare occurrence, might take place with sufficient violence to ionize one of the atoms,—that is, to separate from an atom its electron. If such an occurrence took place, neighboring ether atoms that were not moving so fast, would orient themselves about the charged particles liberated by the collision, and would form, by

condensation, a primitive ion or electron, the size and shape of which would depend upon the sizes and shapes of the charged particles, and the bombardment to which the aggregations would be subjected by other ether particles. Such primitive ions could be built up into the ions of the sub-atoms, and these in turn could form the elements.

We are allowing our fancy to play with these conceptions, with no intention of checking it by forcing it to render these conceptions mathematical by insisting upon working out a system to which numbers may be applied. If such an origin of atoms is thinkable, we can also conceive that when such concentrations were large enough and their masses very great in comparison with that of an ether atom,—when the ion had brought together in small space a very large number of ether atoms, the ion would form so large a target that, if its structure were sufficiently compact it would receive the impact from ether atoms from all directions, even though individual ether atoms, not so compacted, might actually encounter one another but rarely. Two such aggregations, close together, would partially shield each other from bombardment from the space between them, the shielding being greater, the greater the lengths of the free paths of the individual ether atoms. The amount of the shielding must under these circumstances be determined by purely geometrical laws, and it would appear that, if the motion of the ether atoms were purely random, the net result of the shielding would follow the inverse square law. Gravitational attraction might thus be explicable as a result of mutual shielding of the masses against ether bombardment. The only forces acting at a distance would be electrical, between the “ultimate” positive and negative particles of which the ether, and all other forms of matter, are composed, gravitation being a secondary result of impact.

Ether, if constructed according to this ideal model, if in Euclidean or Newtonian space, with positive and negative charges exactly opposite as well as exactly equal, assuming the repulsion of two like charges to be exactly equal to the attraction of two unlike charges, would of necessity be an expanding ether, no matter how vast its extent. One consequence of such an ether would seem to be an expanding universe, as has been suggested by some of the recent mathematical theories which started out with the premise that the Michelson Moreley experiment must, because of the structure of

the Universe, give no observable measurement of motion through the ether.

This system does not extend so far as to include any intelligible scheme for bringing ultimate particles into being or destroying them. It does not explain when or how the universe was created, how long it will last, whether the creation process is continuous, or whether material things are, in last analysis, autochthonous. It leaves such matters entirely out of the scope of mechanistic schemes. The riddle "When is a particle not a particle" is not answered or answerable by Newtonian Mechanics. We may deal mechanistically with the separation of charges and the subdivision of masses into their smallest natural units, but not with their creation or annihilation.

TABLE 1
Some Periodic Properties of the Elements

| Element | Atomic Number | Inter- national Atomic Weight | Atomic Volume | M.P. | B.P. | Valence |
|---------|------------------|----------------------------------------|------------------|---------|--------|--------------|
| | | | | °C. | °C. | |
| H | 1 | 1.008 | 1. | -259 | -258.8 | 1 |
| He | 2 | 4. | 2.36 | -271.9 | -268.9 | 0 |
| Li | 3 | 6.94 | 1.09 | 186 | 1200 | 1 |
| Be | 4 | 9.02 | .421 | 1350 | — | 2 |
| B | 5 | 10.82 | .403 | 2000? | 2550 | 3 |
| C | 6 | 12. | .299 | Sub | 3500? | 4 |
| N | 7 | 14.008 | 1.202 | -209.9 | -195.8 | 3 or 5 |
| O | 8 | 16 | .957 | -218.4 | -183 | 2 |
| F | 9 | 19 | 1.06 | -223 | -187 | 1 |
| Ne | 10 | 20.2 | 2.228 | -248.67 | -245.9 | 0 |
| Na | 11 | 22.997 | 1.929 | 97.5 | 880 | 1 |
| Mg | 12 | 24.32 | 1.21 | 651 | 1110 | 2 |
| Al | 13 | 26.97 | .868 | 660 | 1800 | 3 |
| Si | 14 | 28.06 | 1.055 | 1420 | 2600 | 4 |
| P | 15 | 31.027 | 1.14 | 44.1 | 280 | 3 or 5 |
| S | 16 | 32.064 | 1.316 | 119. | 4446 | 2 or 6 |
| Cl | 17 | 33.457 | 1.43 | -101.6 | -34.6 | 1 |
| A | 18 | 39.91 | 2.05 | -189.2 | -185.7 | 0 |
| K | 19 | 39.096 | 3.77 | 62.3 | 760 | 1 |
| Ca | 20 | 40.07 | 2.246 | 810 | 1170 | 2 |
| Sc | 21 | 45.10 | — | 1200 | 2400 | 3 |
| Ti | 22 | 48.1 | .939 | 1800? | 3000? | 3 or 4 |
| V | 23 | 50.96 | .746 | 1710 | 3000 | 3 or 5 |
| Cr | 24 | 52.01 | .631 | 1615 | 2200 | 2, 3, or 6 |
| Mn | 25 | 54.93 | .637 | 1260 | 1900 | 2, 4, 6 or 7 |
| Fe | 26 | 55.84 | .619 | 1535 | 3000 | 2 or 3 |
| Co | 27 | 58.94 | .577 | 1480 | 2900 | 2 or 3 |
| Ni | 28 | 58.69 | .574 | 1452 | 2900 | 2 or 3 |
| Cu | 29 | 63.57 | .619 | 1083 | 2300 | 1 or 2 |
| Zn | 30 | 65.38 | .787 | 419.4 | 907 | 2 |
| Ga | 31 | 69.72 | 1.026 | 29.75 | 1600? | 3 |
| Ge | 32 | 72.66 | 1.284 | 958 | 2700 | 4 |
| As | 33 | 74.96 | — | Sub | 615 | 3 or 5 |
| Se | 34 | 79.2 | 1.51 | 220 | 688 | 2, 4 or 6 |
| Br | 35 | 79.916 | 1.684 | -7.2 | 58.8 | 1 |
| Kr | 36 | 82.9 | 2.307 | -169 | -151.8 | 0 |
| Rb | 37 | 85.44 | 4.649 | 38.5 | 700 | 1 |
| Sr | 38 | 87.63 | 2.912 | 800 | — | 2 |

TABLE 1—*Continued*

| Element | Atomic Number | Inter- national Atomic Weight | Atomic Volume | M.P. | B.P. | Valence |
|---------|------------------|----------------------------------------|------------------|-------|--------|--------------|
| | | | | °C. | °C. | |
| Y | 39 | 88.9 | 1.667 | 1490 | 2500 | 3 |
| Zr | 40 | 91 | 1.223 | 1700 | 2900? | 4 |
| Nb | 41 | 91.3 | .956 | 1950 | 3300? | 3 |
| Mo | 42 | 96 | .822 | 2620 | 3700 | 3, 4 or 6 |
| Ma | 43 | — | — | 2300 | — | — |
| Ru | 44 | 101.7 | — | 2450 | 2700? | 2, 4, 6 or 8 |
| Rh | 45 | 102.91 | — | 1955 | 2500? | 3 |
| Pd | 46 | 106.7 | — | 1555 | 2200 | 2 or 4 |
| Ag | 47 | 107.88 | .889 | 960.5 | 1950 | 1 |
| Cd | 48 | 112.41 | 1.114 | 320.9 | 767 | 2 |
| In | 49 | 114.8 | 1.342 | 155 | 1450? | 3 |
| Sn | 50 | 118.70 | 1.767 | 231.9 | 2260 | 2 or 4 |
| Sb | 51 | 121.77 | — | 630 | 1380 | 3 or 5 |
| Te | 52 | 127.5 | — | 452 | 1390 | 4 or 6 |
| I | 53 | 126.932 | 2.149 | 113.5 | 184.4 | 1 |
| X | 54 | 130.2 | 3.061 | —140 | —109.1 | 0 |
| Cs | 55 | 132.81 | 5.701 | 26.4 | 670 | 1 |
| Ba | 56 | 137.37 | 3.272 | 850 | 1140 | 2 |
| La | 57 | 138.90 | 1.938 | 826 | 1800 | 3 |
| Ce | 58 | 140.25 | 1.745 | 640 | 1400 | 3 or 4 |
| Pr | 59 | 140.92 | 1.851 | 940 | — | 3 |
| Nd | 60 | 144.27 | 1.763 | 840 | — | 3 |
| Il | 61 | — | — | — | — | 3 |
| Sm | 62 | 150.43 | 1.667 | 1300? | — | 3 |
| Eu | 63 | 152. | — | — | — | 3 |
| Gd | 64 | 157.26 | — | — | — | 3 |
| Tb | 65 | 159.2 | — | — | — | 3 |
| Dy | 66 | 162.52 | — | — | — | 3 |
| Ho | 67 | 163.4 | — | — | — | 3 |
| Er | 68 | 167.7 | — | — | — | 3 |
| Tm | 69 | 169.4 | — | — | — | 3 |
| Yb | 70 | 173.6 | — | — | — | 3 |
| Lu | 71 | 175 | — | — | — | 3 |
| Hf | 72 | 180.8 | 1.174 | 1700 | 3200? | 3 |
| Ta | 73 | 181.5 | .938 | 2850 | 4100? | 5 |
| W | 74 | 184 | — | 3400 | — | 6 |
| Re | 75 | — | .773 | 3000 | — | — |
| Os | 76 | 190.8 | .737 | 2700 | 5300? | 2, 3, 4 or 8 |
| Ir | 77 | 193.1 | .744 | 2350 | 4800? | 3 or 4 |
| Pt | 78 | 195.23 | .788 | 1755 | 4300 | 2 or 4 |

TABLE 1—*Concluded*

| Element | Atomic Number | Inter- national Atomic Weight | Atomic Volume | M.P. | B.P. | Valence |
|---------|------------------|----------------------------------------|------------------|--------|-------|---------|
| | | | | °C. | °C. | |
| Au | 79 | 197.2 | 1.063 | 1063 | 2600 | 1 or 3 |
| Hg | 80 | 200.61 | 1.201 | -38.87 | 356.9 | 1 or 2 |
| Tl | 81 | 204.39 | 1.482 | 303.5 | 1650 | 3 |
| Pb | 82 | 207.20 | 1.570 | 327.5 | 1620 | 2 or 4 |
| Bi | 83 | 209 | 1.842 | 271 | 1450 | 3 or 5 |
| Po | 84 | — | — | — | — | — |
| | 85 | — | — | — | — | — |
| Rn | 86 | 222 | — | — | — | 0 |
| | 87 | — | — | — | — | — |
| Ra | 88 | 225.95 | — | 960 | 1140 | 2 |
| | 89 | — | — | — | — | — |
| Th | 90 | 232.15 | 1.728 | 1845 | 3000? | 4 |
| | 91 | — | — | — | — | — |
| U | 92 | 238.17 | — | — | — | 4 or 6 |

TABLE 2
The Elements Arranged in Chemical Groups

| H. Valence | 1 | 2 | 3 | 4 | 5 | 6 | 7 | Valence | Group |
|------------|------|-------|-------|-------|-------|-------|-------|--------------|-------|
| 1 | 1 H | 3 Li | 11 Na | 19 K | 37 Rb | 55 Cs | 87 | 1 | 1 |
| 2 | | 4 Be | 12 Mg | 20 Ca | 38 Sr | 56 Ba | 88 Ra | 2 | 2 |
| | | | | | | 57 La | | 3 | |
| | | | | | | 58 Ce | | 3 | |
| | | | | | | 59 Pr | | 3 | |
| | | | | | | 60 Nd | | 3 | |
| | | | | | | 61 Il | | 3 | |
| | | | | | | 62 La | | 3 | |
| | | | | | | 63 Eu | | 3 | |
| 3 | | 5 B | 13 Al | 21 Sc | 39 Yt | 64 Gd | 89 | 3 | 3 |
| | | | | | | 65 Tb | | 3 | |
| | | | | | | 66 Ds | | 3 | |
| | | | | | | 67 Ho | | 3 | |
| | | | | | | 68 Er | | 3 | |
| | | | | | | 69 Tm | | 3 | |
| | | | | | | 70 Yb | | 3 | |
| | | | | | | 71 Lu | | 3 | |
| 4 | | 6 C | 14 Si | 22 Ti | 40 Zn | 72 Hf | 90 Th | 4 | 4 |
| | | | | 23 Va | 41 Nb | 73 Ta | 91 | 3 or 5 | 5' |
| | | | | 24 Cr | 42 Mo | 74 W | 92 U | 3, 4 or 6 | 6' |
| | | | | 25 Mn | 43 Ma | 75 Re | | 3, 4, 6 or 7 | 7' |
| | | | | 26 Fe | 44 Ru | 76 Os | | 2 or 3 | |
| | | | | 27 Co | 45 Rh | 77 Ir | | 2 or 3 | 8' |
| | | | | 28 Ni | 46 Pd | 78 Pt | | 2 or 3 | |
| | | | | 29 Cu | 47 Ag | 79 Au | | 1 | 1' |
| | | | | 30 Zn | 48 Cd | 80 Hg | | 2 | 2' |
| | | | | 31 Ga | 49 In | 81 Tl | | 3 | 3' |
| | | | | 32 Ge | 50 Sn | 82 Pb | | 4 | 4' |
| 3 | | 7 N | 15 P | 33 As | 51 Sb | 83 Bi | | 3 or 5 | 5 |
| 2 | | 8 O | 16 S | 34 Se | 52 Te | 84 | | 2, 4 or 6 | 6 |
| 1 | | 9 F | 17 Cl | 35 Br | 53 I | 85 | | 1 | 7 |
| 0 | 2 He | 10 Ne | 18 A | 36 Kr | 54 X | 86 Nt | | 0 | 8 |

TABLE 3

| Atomic Number | Element | International Atomic Weights | Isotopes In order of prevalence |
|---------------|---------|------------------------------|------------------------------------|
| 1 | H | 1.008 | 1 |
| 2 | He | 4. | 4 |
| 3 | Li | 6.94 | 7, 6 |
| 4 | Be | 9.02 | 9 |
| 5 | B | 10.82 | 11, 10 |
| 6 | C | 12. | 12. |
| 7 | N | 14.008 | 14. |
| 8 | O | 16. | 16 |
| 9 | F | 19. | 19 |
| 10 | Ne | 20.2 | 20, 22 |
| 11 | Na | 23 | 23 |
| 12 | Mg | 24.32 | 24, 25, 26 |
| 13 | Al | 26.96 | 27 |
| 14 | Si | 28.06 | 28, 29, 30 |
| 15 | P | 31.02 | 31 |
| 16 | S | 32.06 | 32 |
| 17 | Cl | 35.46 | 35, 37 |
| 18 | A | 39.9 | 40, 36 |
| 19 | K | 39.10 | 39, 41 |
| 20 | Ca | 40.07 | 40, 44 |
| 21 | Sc | 45.1 | 45 |
| 22 | Ti | 48.1 | 48 |
| 23 | V | 51.0 | 51 |
| 24 | Cr | 52 | 52 |
| 25 | Mn | 54.93 | 55 |
| 26 | Fe | 55.84 | 56, 54 |
| 27 | Co | 58.97 | 59 |
| 28 | Ni | 58.68 | 58, 60 |
| 29 | Cu | 63.57 | 63, 65 |
| 30 | Zn | 65.38 | 64, 66, 68, 70 |
| 31 | Ga | 69.72 | 69, 71 |
| 32 | Ge | 72.38 | 70, 72, 74 |
| 33 | As | 75 | |
| 34 | Se | 79.2 | 80, 78, 76, 82, 77, 74 |
| 35 | Br | 79.92 | 79, 81 |
| 36 | Kr | 82.92 | 84, 86, 82, 83, 80, 78 |
| 37 | Rb | 85.45 | 85, 87 |
| 38 | Sr | 87.63 | 88, 86 |
| 39 | Y | 89 | 89 |
| 40 | Zr | 91 | |
| 41 | Nb | 93.1 | |
| 42 | Mo | 96 | |
| 43 | Ma | Ma | |
| 44 | Ru | 101.7 | |
| 45 | Rn | 102.91 | |
| 46 | Pd | 106.7 | |

TABLE 3—*Concluded*

| Atomic Number | Element | International Atomic Weights | Isotopes In order of prevalence |
|------------------|---------|---------------------------------|---------------------------------------------|
| 47 | Ag | 107.88 | 107, 109 |
| 48 | Cd | 112.41 | |
| 49 | In | 114.8 | 115 |
| 50 | Sn | 118.7 | 120, 118, 116, 124, 119, 117, 122, 121 |
| 51 | Sb | 121.77 | 121, 123 |
| 52 | Te | 127.5 | |
| 53 | I | 126.93 | 127 |
| 54 | X | 130.2 | 129, 132, 131, 134, 136, 130, 128, 124, 126 |
| 55 | Cs | 132.81 | 133 |
| 56 | Ba | 137.37 | 138 |
| 57 | La | 138.91 | 139 |
| 58 | Ce | 140.25 | 140 |
| 59 | Pr | 140.92 | 141 |
| 60 | Nd | 144.27 | (142-150) |
| 61 | Il | | |
| 62 | Sm | 150.43 | |
| 63 | Eu | 152 | |
| 64 | Gd | 157.26 | |
| 65 | Tb | 159.2 | |
| 66 | Ds | 162.52 | |
| 67 | Ho | 163.4 | |
| 68 | Er | 167.7 | (164-176) |
| 69 | Tu | 169.4 | |
| 70 | Yb | 173.5 | |
| 71 | Lu | 175.0 | |
| 72 | Hf | | |
| 73 | Ta | 181.5 | |
| 74 | U | 184 | |
| 75 | Re | | |
| 76 | Os | 190.8 | |
| 77 | Ir | 193.1 | |
| 78 | Pt | 195.23 | |
| 79 | Au | 197.2 | |
| 80 | Hg | 200.61 | (197-200), 202, 204 |
| 81 | Tl | 204.4 | |
| 82 | Pb | 207.2 | |
| 83 | Bi | 209 | |
| 84 | Po | | |
| 85 | | | |
| 86 | Rd | 222 | |
| 87 | | | |
| 88 | Ra | 226 | |
| 89 | | | |
| 90 | Th | 232.15 | |
| 91 | | | |
| 92 | U | 238.17 | |

TABLE 4
Types of Series of Spectral "Levels"

| n | Molecule | | Level, in terms of ν |
|-------|----------|-------|--------------------------------------------------------------------------------------------------------------------------------------------------------------|
| A | | | |
| 1 | a | | $N \div a^2$ |
| 2 | a | a | $N \div (2a)^2$ |
| 3 | aa | a | $N \div (3a)^2$ |
| 4 | aa | aa | $N \div (4a)^2$ |
| 5 | aaa | aa | $N \div (5a)^2$ |
| n | | | $N \div (na)^2$ |
| Limit | | | 0 |
| B | | | |
| 1 | b | | $N \div b^2$ |
| 2 | b | b | $N \div (2b)^2$ |
| 3 | bb | b | $N \div (3b)^2$ |
| 4 | bb | bb | $N \div (4b)^2$ |
| 5 | bbb | bb | $N \div (5b)^2$ |
| n | | | $N \div (nb)^2$ |
| Limit | | | 0 |
| C | | | |
| 1 | | | |
| 2 | b | b | $N \div (2b)^2$ |
| 3 | ab | b | $N \div (a + 2b)^2$ |
| 4 | ab | ba | $N \div (2a + 2b)^2$ |
| 5 | aab | ba | $N \div (3a + 2b)^2$ |
| n | | | $N \div [(n - 2)a + 2b]^2$ |
| Limit | | | 0 |
| D | | | |
| 2 | b | a | $N \left[\frac{1}{b^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} \right]$ |
| 3 | ab | a | $N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} \right]$ |
| 4 | ab | ab | $N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} - \frac{1}{(2a + b)^2} + \frac{1}{(2a + 2b)^2} \right]$ |
| 5 | aab | ab | $N \left[\frac{1}{b^2} - \frac{1}{2b^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{2a^2} - \frac{1}{(2a + b)^2} \right] + N \frac{1}{(2b + 3a)^2}$ |
| 6 | aab | aba | $N \left[\dots \right] + N \frac{1}{(2b + 4a)^2}$ |
| Limit | | | $N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} - \frac{1}{(2a + b)^2} \right]$ |
| E | | | |
| 2 | b | a | $N \left[\frac{1}{b^2} + \frac{1}{(2a)^2} - \frac{1}{a^2} \right]$ |
| 3 | ab | a | $N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} \right]$ |
| 4 | ab | aa | $N \left[\frac{1}{b^2} - \frac{1}{(2b)^2} + \frac{1}{(2b + a)^2} - \frac{1}{a^2} + \frac{1}{(2a)^2} - \frac{1}{(3a)^2} + \frac{1}{(4a)^2} \right]$ |
| 5 | aab | aa | |
| 6 | aab | aaa | |

TABLE 5
calculated/calculated Lines and Levels of the Primary Spectrum of Hydrogen

TABLE 7
Regular Progressions of Quantum Numbers in Hydrogen

| | Molecules | | ν | q | Diff. | Mean b |
|---|-----------|-------|-----------|------------|------------|-----------|
| A | a | | 109678 | 1 | | |
| | a | a | 27419.50 | 2 | 1 | |
| | aa | a | 12186.44 | 3 | 1 | |
| | aa | aa | 6854.87 | 4 | 1 | |
| | aaa | aa | 4387.12 | 5 | 1 | |
| | aaa | aaa | 3046.61 | 6 | 1 | |
| | $aaaa$ | aaa | 2238 32 | 7 | 1 | |
| B | b | b | 29327.43 | 1.933850 | | .966925 |
| | ab | b | 12708.33 | 2.937754 | 1 003904 | .968877 |
| | ab | ba | 7055 98 | 3.943584 | 1.005830 | .971292 |
| | aab | ba | 4480 17 | 4.947804 | 1.001220 | .973902 |
| | aab | baa | (3094.71) | (5.953184) | (1 005380) | (.976592) |
| C | b | | 117743 | 965144 | | .965144 |
| | b | b | 29327 34 | 1.933850 | .968706 | .966925 |
| | bb | b | 12989 30 | 2.905806 | .971956 | .968602 |
| | bb | bb | 7280.79 | 3 881708 | .975902 | .970427 |
| | bbb | bb | (4642) | (4.860535) | (.978827) | (.972107) |

TABLE 9
Leading Levels of Curtis' Helium Bands

| Level | ν | q | Diff | Molecule | | Sub-Atomic Radii | |
|--------------------|---------|-------|-------|-------------------|--------------|------------------|-----------------|
| First Band System | | | | | | | |
| 1S | 34301 8 | 1 788 | | $c_2'c_2'$ | $c_2'c_2'$ | $c_2' = .447$ | |
| 2S | 13893 1 | 2 810 | 1 022 | $a_1(c_2''c_2'')$ | $c_2''c_2''$ | $c_2'' = .4525$ | |
| 3S | 7524 6 | 3 818 | 1 008 | $a_1($ | $)a_1$ | $= .4545$ | |
| 4S | 4713 3 | 4 824 | 1 006 | $a_1a_1($ | $)a_1$ | $= .4560$ | |
| 1P | 29715 2 | 1 928 | | $(b_2b_2$ | $b_2b_2)$ | $b_2 = .482$ | |
| 2P | 12794 5 | 2 928 | 1 000 | $a_1($ | $)$ | $= .482$ | |
| 3P | 7108 8 | 3 928 | 1 000 | $a_1($ | $)a_1$ | $= .482$ | |
| 4P | 4516 3 | 4 928 | 1 000 | $a_1a_1($ | $)a_1$ | $= .482$ | |
| 2Z | 12734 0 | 2 935 | | $a_1'(b_2b_2$ | $b_2b_2)$ | $b_2 = .4822$ | $a_1' = 1 .006$ |
| 3Z | 7080 0 | 3 936 | 1 001 | $a_1'($ | $)a_1$ | $= .4822$ | $= 1 .007$ |
| 2X | 12533 0 | 2 958 | | $a_1'(b_2'b_2'$ | $b_2'b_2')$ | $b_2' = .488$ | $a_1' = 1 .006$ |
| 2D | 12080 6 | 3 013 | | a_1a_1' | a_1' | $a_1' = 1 .0065$ | |
| Second Band System | | | | | | | |
| 1S | 31958 1 | 1 853 | | $a_1'c_2$ | c_2 | $c_2 = .4235$ | $a_1' = 1 .006$ |
| 1P | 28423 4 | 1 964 | | $a_1(b_2$ | $b_2)$ | $b_2 = .482$ | |
| 2P | 12481 4 | 2 964 | 1 000 | $a_1($ | $)a_1$ | $= .482$ | |
| 3P | 6978 5 | 3 964 | 1 000 | $a_1a_1($ | $)a_1$ | $= .482$ | |
| 4P | 4448 4 | 4 965 | 1 001 | $a_1a_1($ | $)a_1a_1$ | $= .482$ | |
| 2Z | 12580 | 2 953 | | $a_1(b_2'b_2'$ | $b_2'b_2')$ | $b_2' = .4882$ | |
| 2X | 12414 2 | 2 972 | | $a_1(b_2'$ | $b_2')a_1$ | $b_2' = .486$ | |
| 2D | 12040 | 3 018 | | $a_1'a_1'$ | a_1' | $a_1' = 1 .006$ | |

TABLE 10
Hopfield's Ultraviolet Helium Bands

| λ | ν | ν π level | Sum | 151229- π level |
|--------------|--------|----------------------|--------|---------------------|
| 722 | 138504 | 12746 | 151250 | 138483 |
| 694 | 144092 | 7093 | 151185 | 144136 |
| 682 | 146627 | 4510 | 151137 | 146779 |
| 675 | 148148 | 3118 | 151266 | 148111 |
| 671 | 149031 | 2283 | 151314 | 148946 |
| 669 | 149477 | 1744 | 151221 | 149475 |
| Average..... | | | 151229 | |

TABLE 11
*Dimensions of Sub-Atoms of Helium Derived by Analysis of Quantum
 Numbers of the Normal Spectral Levels*

| Level | ν | q | Diff. | Molecule | Approximate Atomic Radii |
|-------|-------|-----|-------|----------|--------------------------|
|-------|-------|-----|-------|----------|--------------------------|

| Parhelium | | | | | |
|-------------|----------|--------|--------|-------------------|---------------------|
| 1 σ | 38454.71 | 1.6888 | | (c_2c_2) | $c_2 = .4222$ |
| 2 σ | 15073.87 | 2.6974 | 1.0086 | $a_1($) | .4243 |
| 3 σ | 8012.53 | 3.6999 | 1.0015 | $a_1($) a_1 | .4250 |
| 4 σ | 4963.63 | 4.7007 | 1.0008 | $a_1a_1($) a_1 | .4252 |
| 1 π | 29223.88 | 1.9372 | | ($b_2'b_2$) | b_2 (mean) = 4843 |
| 2 π | 12746.08 | 2.9334 | .9952 | $a_1($) | 4834 |
| 3 π | 7093.59 | 3.9321 | .9987 | $a_1($) a_1 | .4830 |
| 4 π | 4509.96 | 4.9314 | .9993 | $a_1a_1($) a_1 | 4829 |
| 2 δ | 12209.10 | 2.9972 | | a_1a_2 | |
| 3 δ | 6866.16 | 3.9967 | .9995 | $a_1a_1a_2$ | |
| 4 δ | 4393.49 | 4.9964 | .9997 | $a_1a_1a_2$ | |
| 3 φ | 6858.39 | 3.9989 | | a_1a_1 | |
| 4 φ | 4389.21 | 4.9988 | .9999 | $a_1a_1a_1$ | |

| Orthohelium | | | | | |
|-------------|----------|--------|--------|------------------------|-----------------|
| 1S | 32032.51 | 1.8504 | | ($c_2'''c_2'''$) | $c_2''' = 4626$ |
| 2S | 13444.23 | 2.8561 | 1.0057 | $a_1($) a_1 | .4640 |
| 3S | 6369.82 | 3.8578 | 1.0017 | $a_1($) a_1 | .4644 |
| 4S | 4646.52 | 4.8584 | 1.0006 | $a_1a_1($) a_1 | .4646 |
| 1P | 27175.17 | 2.0089 | | (a_1') a_1' | $a_1' = 1.0044$ |
| 2P | 12100.56 | 3.0106 | 1.0017 | $a_1(a_1'$) a_1' | $a_1' = 1.0053$ |
| 3P | 6817.21 | 4.0110 | 1.0004 | $a_1(a_1'$) a_1' | $a_1' = 1.0055$ |
| 4P | 4367.45 | 5.0112 | 1.0002 | $a_1a_1(a_1'$) a_1' | 1.0056 |
| 2D | 12205.09 | 2.9977 | | a_1a_2 | |
| 3D | 6863.60 | 3.9979 | 1.0002 | $a_1a_1a_2$ | |
| 4D | 4391.76 | 4.9974 | .9995 | $a_1a_1a_2$ | |
| 3F | 6857.1 | 3.9995 | | a_1a_1 | |
| 4F | 4390.0 | 4.9983 | .9988 | $a_1a_1a_1$ | |

TABLE 12
Irregularities in the Levels of He II

| n | Column 1 | Column 2 | Column 3 | Column 4 | Column 5 | q |
|----|-----------|----------|-----------|----------|----------|----------|
| 1 | 438892.88 | | | | 438912.7 | .499885 |
| 2 | 109723.22 | 329186.8 | 438910.02 | 438915.7 | 109724.9 | .999786 |
| 3 | 48765.87 | 390145.6 | 11.47 | 13.8 | 48767.1 | 1.499671 |
| 4 | 27430.80 | 411481.3 | 12 10 | 14 4 | 27431.4 | 1.999566 |
| 5 | 17555.71 | 421354 7 | 10.41 | 11.1 | | |
| 6 | 12191.47 | 426720.9 | 12.37 | 12.9 | 12191.8 | 2.999340 |
| 7 | 8957 00 | 429955.5 | 12.50 | 12.9 | | |
| 8 | 6857 70 | 432054 8 | 12.50 | 12.8 | 6857.9 | 3.999116 |
| 9 | 5418.43 | 433494.1 | 12.53 | 12.8 | | |
| 10 | 4388.93 | 434523.6 | 12 53 | 12.7 | 4389.1 | 4.998862 |
| 11 | 3627.21 | 435285.4 | 12 61 | 12 8 | | |

TABLE 13
Variations in 1π and $1P$ Levels of Helium if the Regular Levels are Substituted for S and D Levels

| $1\pi - 1\pi'$ | $1\pi'$ (calc) | $1\pi - m\delta$ | Regular Series | $1P - mD$ | $1P$ (calc) | $1P - 1P'$ |
|----------------|----------------|------------------|----------------|-----------|-------------|------------|
| 17.63 | 29206 25 | 17014.78 | 12191.47 | 14970 08 | 27161.55 | 13 64 |
| 8 46 | 29215 42 | 22357 72 | 6857.70 | 20311.57 | 27169.27 | 5.90 |
| 4 56 | 29219 32 | 24830.39 | 4388 93 | 22783 41 | 27172 34 | 2.83 |
| 2.70 | 29221.18 | 26173.31 | 3047.87 | 24125.84 | 27173.71 | 1.36 |
| 1.75 | 29222.13 | 26982.88 | 2239 25 | 24935.17 | 27174 42 | .75 |
| 1 20 | 29222 68 | 27508.26 | 1714.42 | 25460.59 | 27175.01 | .16 |
| 92 | 29222 96 | 27868.35 | 1354 61 | 25820.49 | 27175.10 | .07 |
| .84 | 29223.04 | 28125.81 | 1097.23 | 26078 04 | 27175.27 | -.10 |
| 55 | 29223 33 | 28316.53 | 906 80 | 26268.60 | 27175 40 | -.23 |
| 27 | 29223 61 | 28461.64 | 761.97 | 26413 44 | 27175.41 | -.24 |
| 16 | 29223 72 | 28574.47 | 649 25 | 26526.14 | 27175.49 | -.32 |
| 22 | 29223 66 | 28663.85 | 559.81 | 26615 88 | 27175.69 | -.52 |
| | | 28736.11 | 487.66 | | | |
| | | 28795.45 | | | | |
| | | 28844.39 | | | | |
| | | 28883.4 | | | | |
| | | 28921.1 | | | | |
| 1π | 29223.88 | | | | 27175.17 | $1P$ |

TABLE 14
Interpretation of the Principal Levels of Lithium

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|----------------|---------|--------|--------|--------------|-------------|------------------|
| Li I (Fowler) | | | | | | |
| 1 σ | 43486.3 | 1.5881 | | a_1c_3 | c_3 | $c_3 = .2941$ |
| 2 σ | 16280.5 | 2.5955 | 1.0074 | a_1c_3 | c_3a_1 | .2979 |
| 3 σ | 8475.2 | 3.5974 | 1.0019 | $a_1a_1c_3$ | c_3a_1 | 2990 |
| 4 σ | 5187.8 | 4.5979 | 1.0005 | $a_1a_1c_3$ | $c_3a_1a_1$ | 2991 |
| 1 π | 28582.5 | 1.9588 | | $(b_2'b_2')$ | $b_2'b_2'$ | $b_2' = .4897$ |
| 2 π | 12560.4 | 2.9550 | .9967 | $a_1($ | $)$ | .4888 |
| 3 π | 7018.2 | 3.9532 | .9982 | $a_1($ | $)a_1$ | .4882 |
| 4 π | 4473.6 | 4.9514 | .9982 | $a_1a_1($ | $)a_1$ | .4880 |
| 2 δ | 12203.1 | 2.9979 | | $(a_1a_2$ | $a_2a_1)$ | $a_2 = .4989$ |
| 3 δ | 6863.5 | 3.9975 | .9996 | $a_1($ | $)$ | .4987 |
| 4 δ | 4389.6 | 4.9986 | 1.0011 | $a_1($ | $)a_1$ | .4993 |
| 3 φ | 6856.1 | 3.9993 | | a_1a_1 | a_1a_1 | $a_1 = .9993$ |
| 4 φ | 4381.8 | 5.0003 | 1.0010 | $a_1a_1a_1$ | a_1a_1 | 1.0001 |
| Li II (Werner) | | | | | | |
| 2s | 134033. | .9046 | | c_2'' | c_2'' | $c_2'' = .4523$ |
| 3s | 55318. | 1.4085 | .5039 | $a_2($ | $)$ | .4542 |
| 4s | 30097. | 1.9095 | .5010 | $a_2($ | $)a_2$ | .4547 |
| 5s | 18895 | 2.4100 | .5005 | $a_2a_2($ | $)a_2$ | .4550 |
| 2p | 115806 | .9735 | | b_2' | b_2' | $b_2' = .4867$ |
| 3p | 50578 | 1.473 | .4995 | $a_2($ | $)$ | .4865 |
| 4p | 28182 | 1.973 | .5 | $a_2($ | $)a_2$ | .4865 |
| 5p | 17938 | 2.473 | .5 | $a_2a_2($ | $)a_2$ | .4865 |
| 3d | 48834 | 1.4986 | | a_2a_2 | a_2 | $a_2 = .4995$ |
| 4d | 27467 | 1.9983 | .4997 | a_2a_2 | a_2a_2 | .4996 |
| 5d | 17534 | 2.4982 | .4999 | $a_2a_2a_2$ | a_2a_2 | .4996 |
| 4f | 27435 | 1.9994 | | a_2a_2 | a_2a_2 | $a_2 = .4999$ |
| 5f | 17552 | 2.4997 | .5003 | $a_2a_2a_2$ | a_2a_2 | .4999 |

TABLE 14—*Concluded*

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|------------------|------------------------------|--------|-------|---------------|-------------|------------------|
| Li II (Surgiura) | | | | | | |
| 1S | 546703 | .4479 | | c_2' | | $c_2' = .4479$ |
| 2S | 125197 | .9360 | 4881 | c_2''' | c_2''' | $c_2''' = .4680$ |
| 3S | 53491 | 1.4319 | .4959 | $a_2(c_2'''$ | $c_2''')$ | $c_2''' = .4659$ |
| 4S | 30490 | 1.8966 | 4647 | $a_2(c_2'$ | $c_2')$ | $c_2' = .4483$ |
| 5S | 20806 | 2.2859 | .3993 | $a_2c_2'c_2'$ | $c_2'c_2'$ | $c_2' = .4489$ |
| 2P | 106967 | 1.0126 | | a_2'' | a_2'' | $a_2'' = .5063$ |
| 3P | 47943 | 1.5125 | .4999 | $a_2($ | $)$ | $a_2'' = .5063$ |
| 4P | 27083 | 2.0128 | 5003 | $a_2($ | $)a_2$ | $a_2'' = .5064$ |
| 3D | 48839 | 1.4986 | | a_2a_2 | a_2 | $a_2 = .4995$ |
| 4D | 27479 | 1.9978 | .4992 | a_2a_2 | a_2a_2 | .4995 |
| 5D | 17606 | 2.4959 | .4981 | $a_2a_2a_2$ | a_2a_2 | .4992 |
| 6D | 12273 | 2.9894 | .4935 | $a_2a_2a_2$ | $a_2a_2a_2$ | .4982 |
| 4F | 27460 | 1.9985 | | a_2a_2 | a_2a_2 | $a_2 = .4996$ |
| 5F | 17583 | 2.4975 | .4990 | $a_2a_2a_2$ | a_2a_2 | .4995 |
| 6F | 12213 | 2.9967 | 4992 | $a_2a_2a_2$ | $a_2a_2a_2$ | .4995 |
| Li III (Edlen) | | | | | | |
| 1S | 610112 | .4239 | | c_2 | | $c_2 = .4239$ |
| 2P | 108262 | 1.0065 | | a_2' | a_2' | $a_2' = .5003$ |
| 3P | 48330 | 1.5064 | .4999 | | | |
| 4P | 27247 | 2.0063 | 4999 | | | |
| | 987523 | .3333 | | a_3 | | $a_3 = .3333$ |
| | 246892 | .6666 | 3333 | a_3 | a_3 | |
| | 987462 | .3333 | | a_3 | | |
| | 109730 | 1.0000 | | a_3a_3 | a_3 | $a_3 = .3333$ |
| | 987570 = 9×109730 . | | | | | |

TABLE 15
The Levels of Be I
 Triplet System

| | ν | q | Diff. |
|----------------|----------|---------|--------|
| 3S | 23110.22 | 2.1785 | |
| | 10685.1 | 3.2038 | 1.0243 |
| | 6182.6 | 4.2118 | 1.0080 |
| | 4033.8 | 5.2144 | 1.0026 |
| | 2841.9 | 6.2123 | .9979 |
| | 2111.7 | 7.2068 | .9945 |
| | | | |
| P | 53212.86 | 1.4536 | |
| | 12.18 | | |
| | 09.83 | | |
| P | 15497.64 | 2.6603 | |
| | 6.27 | | |
| | 4.28 | | |
| 3D | 13157.50 | 2.8893 | |
| | 7249.3 | 3.8897 | 1.0004 |
| | 4590.0 | 4.8882 | .9985 |
| | 3163.8 | 5.8878 | .9996 |
| | 2315.1 | 6.8829 | .9951 |
| | 1766.5 | 7.8796 | .9967 |
| | 1383.4 | 8.9040 | 1.0244 |
| | 1117.8 | 9.9050 | 1.0010 |
| | 930.4 | 10.8574 | .9524 |
| | | | |
| P [*] | 14756.3 | 2.7262 | |
| | 7.3 | | |
| | 9.2 | | |
| P | 10362.67 | 3.2533 | |
| | 4.71 | | |
| | 8.64 | | |
| D | 18897.22 | 2.4028 | |
| | 7.82 | | |
| | 8.97 | | |

TABLE 15—*Continued*

Singlet System

| | ν | q | Diff. |
|----|----------|---------|--------|
| 2S | 75192.29 | 1.2077 | |
| | 20515.1 | 2.3122 | 1.1045 |
| | 9946.9 | 3.3206 | 1.0184 |
| | 5870.0 | 4.3225 | 1.0019 |
| | 3871.6 | 5.3225 | 1. |
| | 2744.0 | 6.3222 | .9997 |
| | 2045.6 | 7.3223 | 1.0001 |
| | 1583.8 | 8.3126 | .9903 |
| | 1261.9 | 9.3228 | 1.0102 |
| | 1028.9 | 10.3290 | 1.0062 |
| 2P | 32627.0 | 1.8335 | |
| 3D | 10764.84 | 3.1925 | |
| | 6411.1 | 4.1360 | .9435 |
| | 4190.0 | 5.1162 | .9802 |
| | 2941.2 | 6.1066 | .9904 |
| | 2175.1 | 7.1011 | .9945 |
| | 1672.5 | 8.0980 | .9969 |
| | 1325.4 | 9.0967 | .9987 |
| | 1075.6 | 10.0979 | 1.0112 |
| | 890.9 | 11.0955 | .9976 |
| | 749.1 | 12.1001 | 1.0046 |

The Levels of Be III (Edlen and Ericson)

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|----|---------|--------|-------|-------------|-------------|------------------|
| 1S | 1240800 | .2973 | | c_3 | | $c_3 = .2973$ |
| 2P | 243300 | .6713 | | a_3 | a_3 | $a_3 = .3356$ |
| 3P | 108300 | 1.0063 | .3350 | a_3a_3 | a_3 | .3354 |
| 4P | 60900 | 1.3416 | .3353 | a_3a_3 | a_3a_3 | .3354 |
| 5P | 38700 | 1.6834 | .3418 | $a_3a_3a_3$ | a_3a_3 | .3367 |
| 6P | 26800 | 2.0230 | .3396 | $a_3a_3a_3$ | $a_3a_3a_3$ | .3371 |

The Levels of Be IV (calculated)

| ν | q | Diff. | Molecule | | Line Observed | (Edlen) Diff. |
|---------|-----|-------|----------|-------|---------------|---------------|
| 1758680 | .25 | | a_4 | | | |
| 438920 | .50 | .25 | a_4 | a_4 | 1316760 | 324 |
| 195076 | .75 | .25 | a_4a_4 | a_4 | 1560604 | 358 |

TABLE 15—*Concluded*

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|------------------------------------------|----------|--------|-------|-------------|-------------|------------------|
| The Levels of Be II (Paschen and Kruger) | | | | | | |
| 2S | 146881.7 | .8641 | | c_4c_4 | c_4c_4 | $c_4 = .2160$ |
| 3S | 58650.5 | 1.3675 | .5034 | $a_2($ |) | .2166 |
| 4S | 31416.5 | 1.8682 | .5007 | $a_2($ |) a_2 | .2170 |
| 5S | 19545.6 | 2.3688 | .5006 | $a_2a_2($ |) a_2 | .2172 |
| 6S | 13322.6 | 2.8692 | .5004 | | | .2173 |
| 7S | 9655.7 | 3.3703 | .5011 | | | .2176 |
| 2P | 114952.9 | .9768 | | b_4b_4 | b_4b_4 | $b_4 = .2442$ |
| | 46.3 | | | | | |
| 3P | 50385.3 | 1.4754 | .4986 | $a_2($ |) | |
| | 3.5 | | | | | |
| 4P | 28122 | 1.9756 | 5002 | $a_2($ |) a_2 | |
| 5P | 17911.5 | 2.4746 | .4990 | | | |
| 6P | 12396.1 | 2.9778 | .5032 | | | |
| 7P | 9086. | 3.4743 | 4965 | | | |
| 3D | 48828.5 | 1.4987 | | a_2a_2 | a_2 | |
| 4D | 27459.5 | 1.9985 | .4998 | a_2a_2 | a_2a_2 | |
| 5D | 17570.4 | 2.4982 | 4997 | $a_2a_2a_2$ | a_2a_2 | |
| 6D | 12199.7 | | | $a_2a_2a_2$ | $a_2a_2a_2$ | |
| 7D | 8961.7 | | | | | |
| 8D | 6861.3 | | | | | |
| 4F | 27437.7 | | | a_2a_2 | a_2a_2 | |
| 5F | 17559.8 | | | $a_2a_2a_2$ | a_2a_2 | |
| 6F | 12193.6 | | | $a_2a_2a_2$ | $a_2a_2a_2$ | |
| 7F | 8958.6 | | | | | |

TABLE 16

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii | |
|----------------------------|-------------|--------|-------|----------------|----------------|-------------------|---------------|
| The Levels of B I (Sawyer) | | | | | | | |
| 2p | 67082 67 | 1.2787 | | $b_3 c_3'$ | $c_3' b_3$ | $c_3' = .3150$ | $b_3 = .3242$ |
| 3s | 27042 | 2.0139 | | $a_1 (X_3 X_5$ | $X_5 X_3)$ | | |
| 4s | 12075 | 3.0138 | .9999 | $a_1 (X_3 X_5$ | $X_5 X_3) a_1$ | $\div 8 = 2981$ | $= c_3?$ |
| | 19226 | 2.3844 | | a_1 | | | |
| 3d | 12315 | 2.9843 | | | | $\div 10 = .2984$ | $= c_3?$ |
| 4d | 7084 | 3.9225 | .9382 | | | | |
| 5d | 4594 | 4.8861 | .9636 | | | | |

The Levels of B II Triplets (Edlen)

| | | | | | | |
|----|----------|--------|-------|--|--|--|
| 3S | 73122.1 | 1.2250 | | | | |
| 4S | 36545.3 | 1.7328 | .5078 | | | |
| 5S | 21993.2 | 2.2337 | .5009 | | | |
| 2P | 165561.4 | | | | | |
| | 550 | | | | | |
| | 538 | 8141 | | | | |
| 3P | 58900 | | | | | |
| | 896 | 1.3649 | .5518 | | | |
| 4P | 31350.3 | 1.8708 | .5059 | | | |
| 5P | 19561.3 | 2.3684 | .4976 | | | |
| 4F | 27992.5 | 1.9799 | | | | |
| 5F | 17986.1 | 2.4699 | .4900 | | | |
| 6F | 12426.0 | 2.9716 | .5017 | | | |
| 3D | 52246.0 | 1.4492 | | | | |
| 4D | 28817 | 1.9513 | .5021 | | | |
| 5D | 18256.6 | 2.4516 | .5003 | | | |
| | 103984.7 | | | | | |
| | 976.3 | | | | | |
| | 962.3 | 1.0271 | | | | |
| | 21249.8 | 2.2719 | | | | |
| | 240 | | | | | |
| | 219.1 | | | | | |
| | 2410.4 | 6.7449 | | | | |

TABLE 16—*Continued*

| | ν | q | Diff. | Molecule | Sub-Atomic Radii |
|-------------------------------------|---------|--------|-------|-----------|------------------|
| The Levels of B II Singlets (Edlen) | | | | | |
| | 202646 | .7357 | | | |
| | 129249 | | | | |
| | 129249 | .9212 | | | |
| | 102283 | 1.0458 | | | |
| | 74984 | 1.2094 | | | |
| | 66414.3 | 1.2858 | | | |
| | 34711.8 | 1.7778 | .4920 | | |
| | 58544.0 | 1.3687 | | | |
| | 47959.1 | 1.5122 | | | |
| | 27100.0 | 2.0117 | .4995 | | |
| | 27724.5 | 2.1967 | | | |
| | 14990.2 | 2.7068 | | | |
| | 13519.4 | 2.8483 | | | |
| | 4925.0 | 4.7191 | | | |
| The Levels of B IV | | | | | |
| S | 2091500 | .2289 | | c_4' | $c_4' = .2289$ |
| $2P$ | 433300 | .5030 | | a_4 | $a_4 = .2510$ |
| $3P$ | 193400 | .7530 | .2500 | $a_4 a_4$ | $a_4 = .2510$ |
| The Levels of B V | | | | | |
| | 2774333 | .2 | | a_5 | $a_5 = .2$ |
| | 686086 | .4 | .2 | a_5 | $a_5 = .2$ |

TABLE 16—*Concluded*

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|-----------------------------|----------|--------|-------|-------------|-------------|------------------|
| The Levels of B III (Edlen) | | | | | | |
| 2S | 305391.1 | .5989 | | c_3 | c_3 | $c_3 = .2995$ |
| 3S | 125764.6 | .9342 | .3353 | $a_3(c_3$ | $c_3)$ | .3004 |
| 4S | 68235.6 | 1.2681 | .3339 | $a_3($ | $)a_3$ | .3007 |
| 5S | 42774.9 | 1.6017 | .3336 | $a_3a_3($ | $)a_3$ | .3008 |
| 2P | 257572.6 | | | | | |
| | 538.5 | .6527 | | b_3 | b_3 | $b_3 = .3264$ |
| 3P | 112981.9 | | | | | |
| | 971.7 | .9856 | .3329 | $a_3(b_3$ | $b_3)$ | $b_3 = .3262$ |
| 4P | 63100.1 | 1.3187 | .3331 | $a_3($ | $)a_3$ | .3260 |
| 5P | 40212.1 | 1.6519 | .3332 | $a_3a_3($ | $)a_3$ | .3260 |
| 3D | 109861.1 | .9994 | | a_3a_3 | a_3 | $a_3 = .3331$ |
| 4D | 61794.7 | 1.3329 | .3335 | a_3a_3 | a_3a_3 | .3332 |
| 5D | 39541.8 | 1.6658 | .3329 | $a_3a_3a_3$ | a_3a_3 | .3332 |
| 4F | 61731.9 | 1.3332 | | a_3a_3 | a_3a_3 | $a_3 = .3333$ |
| 5F | 39516.6 | 1.6664 | .3332 | $a_3a_3a_3$ | a_3a_3 | .3333 |
| 6F | 27441.4 | 1.9997 | .3333 | $a_3a_3a_3$ | $a_3a_3a_3$ | .3333 |
| 5G | 39503.9 | 1.6667 | | $a_3a_3a_3$ | a_3a_3 | $a_3 = .3333$ |
| 6G | 27433.6 | 1.9999 | .3332 | $a_3a_3a_3$ | $a_3a_3a_3$ | .3333 |

TABLE 17

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii | |
|-----------------------------------------------------|------------------------------------|--------------------------------------|-------|--------------------------------------------------------------|----------------------------------------------------------|----------------------------------------------|----------------------------------------------------------------|
| The Levels of C I (Paschen and Kruger) (Rearranged) | | | | | | | |
| 2S | 69231 0 | 1 2586 | | | | | |
| 2D | 80686 | 1 1607 | | | | | |
| 2P | 90836 63 5 78 3 | 1 0988 | | | | | |
| 3p | 30486 9 527 0 547 0 28898 | 1 8967 1 8955 1 8948 1 9482 | | $b_2b_2c_2$ $b_2b_2c_2$ $b_2b_2c_2$ $b_2b_2b_2$ | $c_2b_2b_2$ $c_2b_2b_2$ $c_2b_2b_2$ $b_2b_2b_2$ | $c_2 = 2994$ $c_2 = 2994$ $c_2 = 2994$ | $b_2 = .3245$ $b_2 = .3241$ $b_2 = 3240$ $b_2 = 3247$ |
| 4p | 12732 4 12762 8 12777 9 | 2 9349 3 9315 2 9297 | | $a_1(b_2b_2b_2)$ $a_1(b_2b_2b_2)$ $a_1(b_2b_2b_2)$ | $b_2b_2b_2$ $b_2b_2b_2$ $b_2b_2b_2$ | | .3225 3219 3216 |
| 5p | 7091 8 7130 8 7146 | 3 9326 3 9218 3 9177 | | $a_1(b_2b_2b_2)$ $a_1(b_2b_2b_2)$ $a_1(b_2b_2c_2')$ | $b_2b_2b_2a_1$ $b_2b_2b_2a_1$ $c_2'b_2b_2a_1$ | $c_2' = 3146$ | .3221 3206 3221 |
| 6p | 4536 0 4579 7 | 4 9172 4 8937 | | $a_1a_1(b_2c_2c_2')$ $a_1a_1(c_2'c_2'b_2)$ | $c_2'b_2b_2a_1$ $b_2c_2'c_2'a_1$ | $c_2' = 3146$ $c_2' = 3127$ | .3221 3221 |
| 7p | 3148 2 3197 1 | 5 9025 5 8571 | | $a_1a_1(c_2'c_2'b_2)$ $a_1a_1(c_2c_2b_2)$ | $b_2c_2'c_2'a_1$ $b_2c_2c_2a_1$ | $c_2' = 3146$ $c_2 = 2995$ | .3221 3221 |
| 8p | 2311 2 2362 | 6 8887 6 8139 | | $a_1a_1a_1(b_2b_2c_2)$ $a_1a_1a_1(c_2c_2c_2)$ | $c_2b_2b_2a_1$ $c_2c_2c_2a_1$ | $c_2 = 2994$ $c_2 = 3033$ | .3225 3225 |
| 9p | 1771 0 1925 5 | 7 8606 7 7448 | | | | | |
| 10p | 1402 8 | 8 8422 | | | | | |
| 4p | 12149 2 | 3 0045 | | a_1a_1 | a_1 | | |
| 5p | 6846 2 | 4 0025 | .9980 | a_1a_1 | a_1a_1 | | |
| 6p | 4388 2 | 4 9994 | .9969 | $a_1a_1a_1$ | a_1a_1 | | |
| 7p | 3049 0 | 5 9476 | .9982 | $a_1a_1a_1$ | $a_1a_1a_1$ | | |
| 8p | 2241 | 6 9958 | .9982 | $a_1a_1a_1a_1$ | $a_1a_1a_1$ | | |

The Levels of C II. Fowler and Selwyn. A

| | | | | | | |
|---|------------------|--------|--|--|--|--|
| P | 196659 595 | 7468 | | | | |
| D | 121728 1 26 9 | .8439 | | | | |
| S | 100164 9 | 1 0464 | | | | |

TABLE 17—Continued

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|----------------------------------------------------|---------------------------------------------|----------------------------|---------------|----------------------------------------|-------------------------------------|----------------------------------------------|
| The Levels of C II. Fowler and Selwyn. A—Concluded | | | | | | |
| <i>P</i> | 86033.9 85992.7 | 1 1291 | | | | |
| <i>S</i> | 80121.1 39424.6 | 1 1700 1 6679 | .4979 | | | |
| <i>P</i> | 64934.3 23.2 34140.3 134.4 | 1 2996 1 7924 | .4928 | b_1b_1 $a_2($ | b_2b_1) | $b_2 = 3249$ |
| <i>D</i> | 51109.0 7.6 28535.1 4.7 18164.2 | 1 4649 1 9605 2 4573 | 4956 .4968 | $a_2(b_2$ a_2a_2 | $b_2)$ a_2 | $a_2 = 4977$ |
| <i>F</i> | 27680.0 17702.5 12282.8 | 1 9906 2 4891 2 9882 | 4985 .4991 | a_2a_2 $a_2a_2a_2$ $a_2a_2a_2$ | a_2a_2 a_2a_2 $a_2a_2a_2$ | $a_2 = 4976$ $a_2 = 4958$ $a_2 = 4980$ |
| <i>D</i> | 12558.0 9193.0 | 2 9912 3 4541 | 4629 | $a_2a_2a_2$ $a_2a_2a_2a_2$ | $a_2a_2a_2$ $a_2a_2a_2$ | $a_2 = 4986$ $a_2 = 4934$ |

The Levels of C II. Fowler and Selwyn. B (incomplete)

| | | | | | | |
|----------|--------------------------------------------------------------------------|------------------|-------|--|--|--|
| <i>P</i> | 206810.7 789.2 760.6 | .7292 | | | | |
| <i>S</i> | 107788.1 | 1 0087 | | | | |
| <i>P</i> | 82850.0 826.2 731.3 40264.4 240.4 194.3 | 1 1506 1 6504 | .4998 | | | |
| <i>D</i> | 68120.2 105.5 080.5 044.2 35056.4 42.1 20.1 34986.7 | 1 2688 1 7688 | .5000 | | | |

TABLE 17—*Continued*

| | ν | q | Diff. | Molecule | Sub-Atomic Radii |
|-------------------------------------------------------------------------|---------------------------------|------------------|-------|----------|------------------|
| The Levels of C II. Fowler and Selwyn. B (incomplete)— <i>Concluded</i> | | | | | |
| <i>S</i> | 65128 0 34049 1 | 1.2977 1 7948 | .4971 | | |
| <i>P</i> | 63389 7 73 4 50 9 | 1.3161 | | | |
| <i>F</i> | 54063 9 49 6 30 0 02 4 | 1 4243 | | | |
| <i>D</i> | 53258 5 52 9 44 2 33 9 | 1 4350 | | | |
| <i>P</i> | 50972 7 51 6 37.0 | 1.4669 | | | |

The Levels of C III. Normal Singlet Terms (Edlen)

| | | | | | |
|-----------|----------|--------|-------|----------------------------|---------------|
| <i>1S</i> | 386159 7 | 5330 | | | |
| <i>3S</i> | 138991 2 | .8883 | .3553 | | |
| <i>4S</i> | 74439 0 | 1.2138 | 3255 | | |
| <i>2P</i> | 283808 3 | .6216 | | | |
| <i>3P</i> | 127228 4 | .9285 | .3069 | | |
| <i>4P</i> | 63762.2 | 1.3111 | .3826 | | |
| <i>5P</i> | 42904 0 | 1 5989 | .2878 | | |
| <i>6P</i> | 29055 1 | 1 9428 | 3439 | | |
| <i>7P</i> | 21276 | 2 2704 | .3276 | | |
| <i>8P</i> | 16242 | 2 5986 | .3282 | | |
| <i>3D</i> | 109678 5 | 1.0003 | | a_3a_2 a_1 | $a_2 = .3334$ |
| <i>4D</i> | 61947 7 | 1.3309 | .3306 | a_3a_2 a_3a_1 | .3327 |
| <i>5D</i> | 39509 3 | 1 6665 | 3356 | $a_2a_3a_1$ a_3a_1 | .3333 |
| <i>6D</i> | 27437 5 | 1 9998 | .3333 | $a_3a_2a_1$ $a_3a_1a_1$ | 3333 |
| <i>7D</i> | 20130 | 2 3348 | .3350 | $a_3a_2a_3a_1$ $a_3a_3a_1$ | .3335 |
| <i>4F</i> | 63458 1 | 1.3158 | | | |
| <i>5G</i> | 39581.7 | 1.6517 | | | |
| <i>6G</i> | 27470.3 | 1 9853 | .3336 | | |

The Levels of C III. Displaced Singlet Terms (Edlen)

| | | | | | |
|-----------|----------|--------|-------|--|--|
| <i>2S</i> | 203639 8 | .6396 | | | |
| <i>3S</i> | 41065.5 | 1.0191 | .3795 | | |

TABLE 17—*Continued*

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|------------------------------------------------------------------------|----------|--------|-------|---------------|-----------|----------------------|
| The Levels of C III. Displaced Singlet Terms (Edlen)— <i>Concluded</i> | | | | | | |
| 2D | 240284 6 | 5999 | | | | |
| 3D | 66440 3 | 9151 | 3152 | | | |
| 4D | 5047 | 1 2553 | 3402 | | | |
| 3P | 53043 | 9658 | | | | |
| 4P | 506 | 1 2985 | 3227 | | | |
| 3P | -23364 | 1 6315 | 3330 | | | |
| 3P | 76154 2 | 8829 | | | | |
| 4P | 7128 | 1 2369 | 3540 | | | |
| 3P | 37300 2 | 1 0378 | | | | |
| 3D | 44791 5 | 1 0016 | | | | |
| 3F | 53470 0 | 9641 | | | | |
| 4F | 338 | 1 3000 | 3359 | | | |
| 5F | -23526 | 1 6347 | 3347 | | | |
| The Levels of C III. Normal Triplet Terms (Edlen) | | | | | | |
| 3S | 147999. | 8611 | | | | |
| 4S | 76775 2 | 1 1957 | .3346 | | | |
| 5S | 46259 9 | 1 5398 | 3441 | | | |
| 6S | 31386 | 1 8698 | 3300 | | | |
| 2P | 333844 6 | | | | | |
| | 20 9 | | | | | |
| | 764 9 | 5734 | | | | |
| 3P | 126505 9 | | | | | |
| | 500 4 | | | | | |
| | 487 6 | 9314 | 3580 | | | |
| 4P | 68415 | 1 2665 | .3351 | | | |
| 3D | 116203 2 | | | | | |
| | 200 4 | | | | | |
| | 197 3 | 9718 | | | | |
| 4D | 64803 0 | | | | | |
| | 784 6 | | | b_2b_2 | b_2b_2 | $b_2 = 3254$ (mean) |
| | 761 1 | 1 3017 | 3299 | | | |
| 5D | 40717 | 1 6416 | .3399 | $a_2(b_2b_2)$ | b_2b_2 | .3271 |
| 6D | 28117 | 1 9755 | .3339 | $a_2($ | $)a_2$ | .3272 |
| 7D | 20608 | 2 3076 | .3321 | $a_2a_2($ | $)a_2$ | .3269 |
| 8D | 15727 | 2 6415 | 3339 | $a_2a_2($ | $)a_2a_2$ | .3271 |
| 4F | 64210 3 | | | | | |
| | 203 8 | | | | | |
| | 194 8 | 1 3074 | | b_2b_2 | b_2b_2 | $b_2 = .3268$ (mean) |
| 5F | 39061 5 | | | $a_2a_2a_2$ | a_2a_2 | |
| | 57 6 | | | | | |
| | 55 3 | 1 6762 | .3688 | | | |

TABLE 17—Continued

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|---------------------------------------------------------------------|---------|--------|-------|---------------|-------------|------------------|
| The Levels of C III. Normal Triplet Terms (Edlen)— <i>Concluded</i> | | | | | | |
| 5 <i>G</i> | 39634 3 | 1 6647 | | $a_2a_2^21_2$ | a_2a_2 | |
| 6 <i>G</i> | 27533 4 | 1 9934 | .3287 | $a_3a_3^21_2$ | $a_3a_3a_3$ | |

The Levels of C III. Displaced Triplet Terms (Edlen)

| | | | | | | |
|----|----------|--------|-------|--|--|--|
| S | 58934.2 | .9425 | | | | |
| 2P | 248784 9 | | | | | |
| | 56.0 | | | | | |
| | 09.2 | .5918 | | | | |
| 3P | 56526 6 | | | | | |
| | 505 5 | | | | | |
| | 468 8 | .9521 | .3603 | | | |
| 4P | 1844. | 1 2852 | .3331 | | | |
| 5P | -22688 | 1 5974 | .3331 | | | |
| 6P | -35743 | 1 9503 | .3320 | | | |
| 3D | 63137 0 | | | | | |
| | 109 5 | | | | | |
| | 070 8 | .9271 | | | | |
| 4D | 4237. | 1 2626 | .3355 | | | |
| | -22548. | 1 5974 | .3348 | | | |
| | -35184. | 1 9317 | .3343 | | | |
| 2P | 77997 9 | | | | | |
| | 963 6 | | | | | |
| | 894 9 | .8776 | | | | |
| 3P | 46069 4 | | | | | |
| | 083 9 | | | | | |
| | 110.2 | .9936 | | | | |
| 3D | 48549 7 | | | | | |
| | 24 7 | .9849 | | | | |
| 4D | -1473 | 1 3185 | .3335 | | | |
| 5D | -24239 | 1 6515 | .3330 | | | |
| 6D | -36728 | 1 9845 | .3330 | | | |
| 3F | 52827 8 | | | | | |
| | 800 1 | | | | | |
| | 765 2 | .9670 | | | | |

The Levels of C IV. (Edlen)

| | | | | | | |
|----|-----------|--------|-------|-------------|----------|---------------|
| 2S | 520187 2 | 4592 | | c_4 | c_4 | $c_4 = .2296$ |
| 3S | 217339 7 | 7105 | .2503 | a_4c_4 | c_4 | .2302 |
| 4S | 118589 8 | 9608 | .2503 | a_4c_4 | c_4a_4 | .2304 |
| 5S | 74805 5 | 1 2111 | .2503 | $a_4a_4c_4$ | c_4a_4 | .2305 |
| 6S | [51390 7] | | | | | |

TABLE 17—*Concluded*

| | ν | q | Diff. | Molecule | | Sub-Atomic Radii |
|-----------------------------------------------|-------------------|--------|-------|-------------|-------------|------------------|
| The Levels of C IV. (Edlen)— <i>Concluded</i> | | | | | | |
| 2P | 455703 3 596 6 | .4907 | | b_1 | b_4 | $b_4 = .2453$ |
| 3P | 200139 1 107 6 | .7405 | .2498 | a_4b_4 | b_4 | .2450 |
| 4P | 111816 5 48 4 | .9904 | 2499 | a_4b_4 | b_4a_4 | 2452 |
| 5P | 71313 9 | 1 2404 | .2500 | $a_4a_4b_4$ | b_4a_4 | 2452 |
| 6P | [49396 8] | | | | | |
| 3D | 195298 6 | 7499 | | a_4a_4 | a_4 | $a_4 = 2499$ |
| 4D | 109835 9 | 9995 | 2496 | a_4a_4 | a_4a_4 | 2499 |
| 5D | [70248 8] | 1 2495 | .2500 | | | |
| 6D | 48806 | 1 4999 | 2504 | | | |
| 4F | 109743 7 | 9999 | | a_4a_4 | a_4a_4 | $a_4 = 25$ |
| 5F | [70235 4] | | | | | |
| 6F | [48773 3] | | | | | |
| 5G | 70229 4 | 1.2499 | | $a_4a_4a_4$ | a_4a_4 | $a_4 = 25$ |
| 6G | [48770 3] | | | | | |
| 6H | 48769 9 | 1 5 | | $a_4a_4a_4$ | $a_4a_4a_4$ | $a_4 = 25$ |
| The Levels of C V. (Edlen) | | | | | | |
| S | 3159600 | 1863 | | c_5 | | $c_5 = 1863$ |
| P• | 677000 | 4025 | | a_5 | a_5 | $a_5 = 2012$ |

TABLE 18
The Levels of Ne II

| ν | q | Diff. | |
|--------|--------|-------|------------------|
| 293763 | .6113 | | $\div 2 = .3056$ |
| 981 | .6119 | | .3059 |
| 76710 | 1.1958 | | $\div 4 = .2989$ |
| 74634 | 1.2123 | | $\div 4 = .3031$ |
| 74116 | | | |
| 73717 | | | |
| 69677 | 1.2546 | | $\div 4 = .3136$ |
| 066 | 1.2602 | | $\div 4 = .3150$ |
| 47572 | 1.5184 | | $\div 5 = .3061$ |
| 350 | | | |
| 167 | | | |
| 47384 | 1.5214 | | $\div 5 = .3043$ |
| 44657 | 1.5671 | | $\div 5 = .3134$ |
| 319 | | | |
| 070 | | | |
| 43926 | | | |
| 42754 | 1.6017 | | $\div 5 = .3203$ |
| 243 | | | |
| 41867 | 1.6185 | | $\div 5 = .3237$ |
| 40811 | 1.6394 | | $\div 5 = .3279$ |
| 39600 | 1.6642 | | $\div 5 = .3328$ |
| 473 | | | |
| 17490 | 2.5041 | | $\div 8 = .3130$ |
| 225 | | | |
| 17163 | 2.5279 | | $\div 8 = .3160$ |
| 14628 | 2.7382 | | $\div 9 = .3042$ |
| 547 | | | |
| 440 | | | |
| 342 | | | |

TABLE 18—*Concluded*

| ν | q | Diff. | |
|-------|--------|-------|-------------------|
| 13593 | 2.8405 | | $\div 9 = .3156$ |
| 13065 | | | |
| 12968 | | | |
| 12819 | | | |
| 13496 | 2.8509 | | $\div 9 = .3167$ |
| 12524 | | | |
| 12997 | 2.9049 | | $\div 9 = .3227$ |
| 776 | | | |
| 594 | | | |
| 13433 | 2.8574 | | $\div 9 = .3175$ |
| 292 | | | |
| 11767 | 3.0530 | | $\div 10 = .3053$ |
| 393 | | | |
| 10995 | | | |
| 10443 | 3.2407 | | $\div 10 = .3240$ |
| 9871 | 3.3333 | | $\div 10 = .3333$ |

TABLE 19
Progressions of K lines in X-ray Spectra

| Atomic number | $K\alpha_2$ | | $K\beta_2$ | |
|---------------|--------------------------------------------|-------|--------------------------------------------|-------|
| | $\left(\frac{\nu}{R}\right)^{\frac{1}{2}}$ | Diff. | $\left(\frac{\nu}{R}\right)^{\frac{1}{2}}$ | Diff. |
| 11 | 8.756 | | | |
| 12 | 9.609 | .853 | | |
| 13 | 10.465 | .856 | | |
| 14 | 11.320 | .855 | | |
| 15 | 12.180 | .860 | | |
| 16 | 13.035 | .855 | | |
| 17 | 13.893 | .858 | | |
| 19 | 15.616 | | | |
| 20 | 16.481 | .865 | | |
| 21 | 17.347 | .866 | | |
| 22 | 18.214 | .861 | | |
| 23 | 19.084 | .870 | | |
| 24 | 19.953 | .869 | | |
| 25 | 20.824 | .871 | | |
| 26 | 21.695 | .871 | | |
| 27 | 22.568 | .873 | | |
| 28 | 23.442 | .874 | 24.767 | |
| 29 | 24.316 | .874 | 25.713 | .946 |
| 30 | 25.191 | .875 | 26.671 | .958 |
| 31 | 26.069 | .878 | 27.629 | .958 |
| 32 | 26.944 | .875 | 28.593 | .964 |
| 33 | 27.820 | .876 | 29.561 | .968 |
| 34 | 28.698 | .878 | 30.526 | .965 |
| 35 | 29.577 | .879 | 31.498 | .968 |
| 36 | | | | |
| 37 | 31.341 | | 33.443 | |
| 38 | 32.223 | .882 | 34.419 | .976 |
| 39 | 33.109 | .884 | 35.401 | .982 |
| 40 | 33.995 | .886 | 36.381 | .980 |
| 41 | 34.883 | .888 | 37.362 | .981 |
| 42 | 35.773 | .890 | 38.347 | .985 |
| 44 | 37.557 | | 40.321 | |
| 45 | 38.451 | .894 | 41.311 | .990 |
| 46 | 39.346 | .895 | 42.305 | .994 |
| 47 | 40.244 | .898 | 43.300 | .995 |
| 48 | 41.144 | .900 | 44.307 | 1.007 |
| 49 | 42.045 | .901 | 45.296 | .989 |
| 50 | 42.949 | .904 | 46.306 | 1.010 |
| 51 | 43.853 | .904 | 47.312 | 1.006 |
| 52 | 44.757 | .904 | 48.315 | 1.003 |
| 53 | 45.664 | .907 | 49.314 | 1.001 |

TABLE 19—*Concluded*

| Atomic number | $K\alpha_2$ | | $K\beta_2$ | |
|---------------|--------------------------------------------|-------|--------------------------------------------|-------|
| | $\left(\frac{\nu}{R}\right)^{\frac{1}{2}}$ | Diff. | $\left(\frac{\nu}{R}\right)^{\frac{1}{2}}$ | Diff. |
| 54 | | | | |
| 55 | 47.487 | | 51.368 | |
| 56 | 48.401 | .914 | 52.370 | .984 |
| 57 | 49.318 | .917 | 53.393 | 1.023 |
| 58 | 50.235 | .917 | 54.419 | 1.026 |
| 59 | 51.169 | .924 | 55.462 | 1.043 |
| 60 | 52.082 | .913 | 56.474 | 1.012 |
| 62 | 53.956 | | 58.545 | |
| 63 | 54.872 | .916 | 59.611 | 1.066 |
| 64 | 55.806 | .924 | 60.664 | 1.053 |
| 65 | 56.760 | .954 | 61.733 | 1.069 |
| 66 | 57.696 | .936 | 62.770 | 1.037 |
| 67 | 58.642 | .946 | | |
| 68 | 59.588 | .946 | 64.847 | |
| 69 | 60.543 | .955 | | |
| 70 | 61.495 | .942 | 66.963 | |
| 71 | 62.461 | .966 | 68.100 | 1.037 |
| 72 | 63.425 | .964 | 69.178 | 1.078 |
| 73 | 64.398 | .963 | 70.275 | 1.097 |
| 74 | 65.340 | .942 | 71.354 | 1.079 |
| 76 | 67.281 | | 73.486 | |
| 77 | 68.273 | .992 | 74.596 | 1.110 |
| 78 | 69.248 | .965 | 75.376 | 1.140 |
| 79 | 70.212 | .968 | 76.859 | 1.123 |
| 81 | 72.231 | | 79.168 | |
| 82 | 73.206 | .970 | 80.322 | 1.154 |
| 83 | 74.260 | .954 | 81.493 | 1.171 |
| 90 | 81.617 | | 89.644 | |
| 92 | 83.420 | | 91.678 | |

TABLE 20
Interpretation of K_{α} Lines

| Atomic number | Element | $\frac{\nu}{R} = a - \frac{X}{a}$ | x | $\frac{x}{a}$ |
|---------------|---------|-----------------------------------|-------|---------------|
| 4 | Be | 7.88 | .2229 | .8916 |
| 5 | B | 13.46 | .1816 | .9080 |
| 6 | C | 20.47 | .1533 | .9198 |
| 7 | N | 28.89 | .1332 | .9324 |
| 8 | O | 38.68 | .1168 | .9344 |
| 9 | F | 49.89 | .1043 | .9387 |
| 10 | Ne | | | |
| 11 | Na | 76.67 | .0860 | .9460 |
| 12 | Mg | 92.34 | .0791 | .9493 |
| 13 | Al | 109.52 | .0733 | .9529 |
| 14 | Si | 128.15 | .0682 | .9548 |

